Angle-DC

Close Down Report

Future Networks

Index

Glossary of Terms

TERM	DEFINITION
AC	Alternating Current.
CAPEX	Capital Expenditure.
CBA	Cost Benefit Analysis.
DC	Direct Current.
DER	Distributed Energy Resource.
DNOs	Distribution Network Operators.
EA	Energy Availability.
ENA	Energy Network Association.
EU	European Union.
FACT	Flexible AC Transmission.
FAT	Factory Acceptance Test.
FEU	Forced Energy Unavailability.
FOR	Forced Outage Rate.
GB	Great Britain.
GHG	Greenhouse gas.
GW	Giga-Watts.
HVDC	High Voltage Direct Current.
HVPD	High Voltage Partial Discharge Ltd.
IGBT	Insulated Gate Bi-Polar Transistor.
kV	Kilo-Volts
LCNI	Low Carbon Network Innovation
LV	Low Voltage
MV	Medium Voltage
MVDC	Medium Voltage DC
MVA	Mega-Volt Amps
MVAr	Reactive Mega-Volt Amps
MW	Mega-Watts
NC	Normally Closed Circuit
NIA	Network Innovation Allowance
NIC	Network Innovation Competition
NO	Normally Open Circuit
NPV	Net Present Value
OHL	Overhead Line
OPEX	Operational Expenditure
PD	Partial Discharge
PM	Project Manager
R&D	Research and Development
RIIO-ED1	Electricity Distribution 1 Regulatory Period

TERM	DEFINITION
SAT	Site Acceptance Test
SDRCs	Successful Reward Delivery Criteria
SEU	Scheduled Energy Unavailability
STATCOM	Static Synchronous Compensator
TRL	Technology Readiness Level
UK	United Kingdom
VSC	Voltage Source Convertor
Wh	Watt-hour
WP	Work Package

1 Project Background

The ANGLE-DC is an innovative project which aims to demonstrate a smart and flexible method for reinforcing distribution networks by converting Alternating Current (AC) assets for Direct Current (DC) operation. ANGLE-DC adapted existing power electronic technology, to build a medium voltage DC (MVDC) link. This link is an effective solution to facilitate the integration of renewable resources and accommodate future demand growth. ANGLE-DC aimed to build the confidence in deploying MVDC technologies, by other UK Distribution Network Operators (DNOs), and trigger the medium voltage DC supply chain. ANGLE-DC had the following overarching objectives:

- Trial the first flexible MVDC link in the Great Britain (GB) distribution system;
- Trial conversion of an AC circuit to DC operation to enhance circuit capacity at the international level;
- Trial real-time holistic circuit condition monitoring of a DC circuit converted from AC to provide the evidence and confidence for DNOs;
- Develop technical guidance, recommendations and policy documents for planning, procurement, operation and control strategy of MVDC converters and MVDC links;

1.1 THE PROBLEMS WHICH NEED TO BE RESOLVED

Compared with the original context and challenges, when the project was proposed and approved by the Authority in 2015/16, the present accelerated pace of distributed renewable development, energy supply security and greater ambition of a net zero network, the Angle-DC solution serves as a strong testimony of the vision and timeliness of this project. All the challenges listed in the original proposal are more relevant under the UK Net Zero strategy.

Increasing demand growth and uptake of distributed energy resources place pressure on the distribution network. Electricity distribution networks need to adapt for the future energy scenarios which aim to reduce CO_2 emissions in the power sector to near zero by 2050. The UK Carbon Plan promotes the electrification of heating and transport and the use of renewable energy sources, which will mainly be connected to distribution networks. Consequently, DNOs face a challenge to accommodate a significant demand growth and Distributed Generation (DG) capacity, which is predicted to nearly double with approximately 21.8 GW in the GB by 2035. Thus, extensive and prohibitively expensive reinforcement of the distribution networks is required to maintain networks within thermal, voltage and fault level constraints and comply with the electricity industry standards.

The creation of new wayleaves for additional distribution circuits and substations is difficult in the UK. Conventional reinforcements typically involve significant costs and additional land requirements. Obtaining way-leave agreements or easements could directly affect the lead time of distribution network expansion schemes. Consequently, this may result in lengthy lead times for renewable connections and a slowing down in the move towards UK Carbon Plan targets. Solutions for future distribution networks need to make the most efficient use of existing assets, this potentially defers or avoids the need for new network reinforcements.

A passive distribution network does not satisfy future network requirements. Renewable resources are intermittent, and their export does not necessarily coincide with local demand requirements. This, along with the inherent uncertainty of future generation and demand, requires distribution networks to be flexible and controllable. The operation of conventional AC distribution networks is mostly passive and is not able to provide the necessary control of power flow magnitude and direction.

Power exchange between two distribution networks is mostly only possible through primary grids. Most GB distribution systems are traditionally operated radially; neighbouring networks are not operated with interconnection as coupling distribution systems may result in thermal ratings, fault level limits and permissible voltage levels being exceeded. However, a direct and controlled power exchange between distribution systems allows the transfer of the excessive power generated by DGs to other load centres. A reliable and controlled interconnection between distribution systems could potentially reduce network losses, enhance the reliability of the system, and reduce customer interruptions by increasing the power supply paths.

1.2 THE METHOD BEING TRIALLED TO SOLVE THE PROBLEM

ANGLE-DC aims to address the aforementioned problems, by building on earlier projects and demonstrate additional benefits from the deployment of MVDC converters, at both ends of an existing circuit, rather than a one site "back-to-back" application with a DC bus. The proposed method can enable power and voltage control over a wider area of influence and increase the capacity of an existing circuit. The following three principles will be trialled in the ANGLE-DC project:

1. Insertion of a flexible MVDC link in a GB distribution system;
2. Conversion of an AC circuit to DC operation;
3. Holistic circuit condition monitoring of a DC circuit converted from AC.

The first principle is to use MVDC converters at both ends of a distribution network interconnector, to control the power through the link and voltage at both distribution systems. This solution will develop a building block for active rather than passive power control between two distribution networks which cannot be operated coupled by an AC circuit due to uncontrolled circulating power and fault levels. This will be the first GB trial of a MVDC link (to our best knowledge the first in Europe).

The second principle is to convert existing AC medium voltage (MV) distribution circuits to DC operation. This solution is anticipated to unlock capacity from the existing circuits which can be used to facilitate integration of renewable resources. This will be the first trial of the method on GB distribution networks.

The third principle demonstrates that AC assets can be used for DC operation by real-time condition monitoring of assets in pre and post DC conversion. Real-time partial discharge (PD) monitoring equipment will be deployed at both ends of the link to assess the performance of AC assets in different loading and DC stress conditions in real-time. To our best knowledge, PD monitoring of DC circuits at medium voltage has not been trialled before in the UK.

1.3 THE DEVELOPMENT OR DEMONSTRATION BEING UNDERTAKEN

An existing 33kV AC circuit between North Wales and Anglesey has been identified as a suitable location for a trial to demonstrate the application of a flexible MVDC link using existing circuits. This circuit connects Bangor (mainland) to Llanfair PG (Anglesey) 33kV substations and comprises both cable sections and overhead line sections.

In the Anglesey area, the volume of renewable generation and the demand for electricity are increasing significantly. The connected and contracted renewable generation connections have reached around 160 MW while the original 33kV circuit has only a secured capacity of 24MWA. Consequently, voltage and thermal rating issues in several locations in Anglesey and North Wales need to be addressed. Additional headroom derived from increased capacity of circuits operating using DC will bring benefits to the wider area and reasonable provision for uncertain future developments.

Furthermore, it is necessary to control power flow on the 33kV circuits between Anglesey and the mainland connecting the two different distribution systems, as the existing 33kV network creates a parallel power flow path with the existing 400kV transmission network. Uncontrolled power flow may exceed the thermal rating of the 33kV Bangor- Llanfair PG circuit, as illustrated in Figure 2 1.

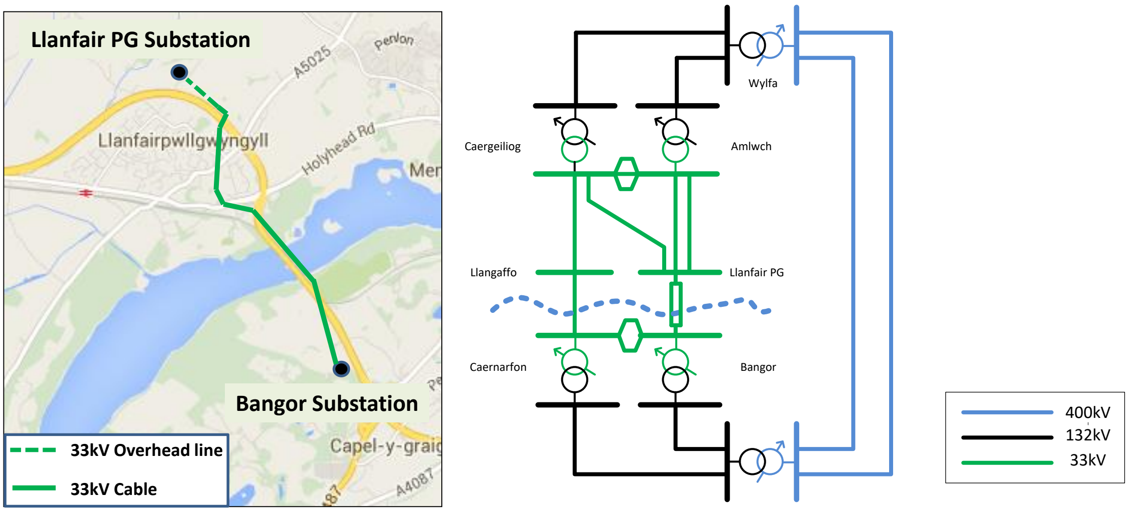


Figure 1-1 Existing 33kV circuit route and schematic diagram between Bangor and Llanfair PG.

Therefore, this circuit represents an appropriate location to demonstrate the viability of an attractive alternative reinforcement technique.

1.4 THE SOLUTIONS

The project aims to prove the viability of converting existing AC circuits to DC operation, by demonstrating that it is practically possible to realise improvements in the control of power flow, voltage profile and increased capacity for a real circuit. Furthermore, practical experience will be acquired (and shared) by way of a prudent approach to design; requirements for testing the existing equipment; proof of the equipment reliability and scheme availability; and improvements obtained in the wider distribution network. By the end of the ANGLE-DC trial, it is anticipated that the MVDC reinforcement solution will be significantly de-risked for future applications.

The solution provides operational benefits to the distribution system on Anglesey by providing an up-rated power corridor to the mainland, while also providing ancillary benefits to the AC distribution network by controlling power flow and regulating voltage at both ends of the circuit. This will potentially allow further connection of low carbon renewable energy sources on the island; and defer the need for further medium voltage AC reinforcements on the island or mainland. It is expected that because the MVDC technology can improve the voltage control in the wider area of the distribution network, operating losses will decrease. Energy losses represent an economic cost to system operation and the savings will reduce the ultimate cost that is borne by the consumers of electricity.

2 Executive Summary

Approved under 2015 Network Innovation Competition mechanism (and modified in 2020), the £14.8M Angle-DC is a national energy innovation flagship project. This ground-breaking project has sought to improve network capacity and performance, using power flow control, by converting an AC interconnector to DC forming a Medium Voltage Direct Current (MVDC) link, so that an increased thermal capacity and better controllability can be achieved by the existing assets.

SP Energy Networks are the leading licensee and have been supported by GE Power Conversion and Cardiff University. Angle-DC has truly revolutionised distribution power flow control, by bringing HVDC technology to the Medium Voltage distribution network, through the delivery of Europe's first operational MVDC link. The active power flow control helps protect to network against the inherent uncertainty of future generation and demand growth.

Angle-DC focused on reducing consumer cost of losses and network reinforcement through:

LOSSES OPTIMISATION – providing control room operators with calculated seasonal and real time setpoints, to reduce network losses to a minimum, even as the spread of load a generation changes across the network.

CAPACITY INCREASE – by optimising power flows, previously heavily loaded circuits are now loaded to lower amounts, releasing capacity for new connections across the Anglesey and north Wales distribution network.

DEFERED WAYLEAVES – by increasing interconnector capacity, and increasing new AC network connections capacity, the need for a significant number of new wayleaves have been avoided. The need for new wayleaves will continued to be reduced throughout RIIO ED2 and beyond.

The Angle-DC project commenced in January 2016, with an initial completion date of April 2022. However, a 15-month extension was later approved by Ofgem, in order to allow the building redesign and to allow the capture and analysis of the operational data.

2.1 BACKGROUND

Electricity distribution networks need to adapt to facilitate future energy decarbonisation, reducing CO_2 emissions in the power sector to Net Zero by 2050. The north Wales and Anglesey electrical distribution networks face challenges from the uptake of Distributed Energy Resources and increasing demand growth, which is placing pressure on the AC distribution networks, designed for passive power flows and centralised generation.

In 2015, there was approximately 145 MW of distributed generation connected, or contracted to connect, in north Wales and on Anglesey, which has increased to 172MW during the ED1 regulatory period. The increase in generation and any increase in demand will cause voltage issues and circuit overloads. Finally, distributed generation is often intermittent and does not necessarily coincide with local demand requirements. The inherent uncertainty of future generation and demand requires power flows, in distribution networks, to be flexible and controllable.

The Angle-DC project was awarded funding through Ofgem's Network Innovation Competition funding mechanism and commenced in January 2016. The project aimed to demonstrate the viability of converting an existing AC interconnector to DC operation, to raise the power transmission capability and control power flows between North Wales and the Island of Anglesey and solve the voltage and circuit overload issues.

2.2 PROJECT SCOPE

ANGLE-DC aimed to address the challenges on Anglesey and north Wales, by demonstrating additional benefits from the deployment of MVDC converters at both ends of an existing circuit by trialling:

1. The insertion of a flexible MVDC link in a 33kV distribution system;
2. The conversion of an AC circuit to DC operation;
3. The holistic circuit condition monitoring of a DC circuit converted from AC.

To complete the three main scope areas above, the project was split into six distinct work packages:

Work Package 1 - Detailed Design

- Conduct detailed system studies, a fresh review of MVDC technologies and supplier engagement.
- Development of technical specifications for the procurement of MVDC link and holistic circuit condition monitoring equipment.
- Development of optimised power flow and protection control strategy.

Work Package 2 - MVDC Link

- All the activities required for manufacturing the MVDC link equipment, site preparation, installation and commissioning the MVDC link.

Work Package 3 - AC System

- All the activities required for the installation and commissioning of a new 33kV AC cable, in parallel with the MVDC circuit, to enable outage and testing under commissioning and different power flow scenarios.

Work Package 4 - Holistic Circuit Condition Monitoring

- All the activities required for manufacturing the monitoring systems equipment, site preparation, installation and commissioning the holistic condition monitoring equipment.

Work Package 5 - Data Analysis

- Continuous monitoring, recording and analysis of the MVDC link performance to build confidence in the MVDC technology.
- Development of technical installation guidance and policy documents for MVDC design and operation.

Work Package 6 - Dissemination

- Review of project learning and dissemination of lessons learnt.

2.3 PROJECT OUTCOMES

The outcomes of the Angle-DC Project show that a fully operational MVDC Link can be deployed successfully on the 33kV distribution network, and they can be used it to manage power flows between a transmission and distribution network. The Method has shown that an MVDC link can reduce network losses and releases significant capacity, on distribution networks, by balancing feeder loads, through real power control. Independent reactive power control has been demonstrated, at each end of the MVDC link, to optimise network voltage within a constantly changing network.

The outcomes of the Factory Acceptance Tests were, that a mixture of current power electronic testing standards can be used to successfully test individual MVDC link items of plant, including the power electronic modules, to ensure the MVDC link, as a system, can be successfully commissioned at the site acceptance stage. The factory testing standards range from those used for HVDC Voltage Source Converter valves to AC power drives and general power electronic testing.

During the MVDC link commissioning tests, good steady state performance was observed, even with voltage step changes occurring at the AC bus. Good dynamic response was also observed when stepping between two high power setpoints in large increments of power. Throughout all the tests, very low levels of DC and AC harmonics were recoded. These results confirmed the MVDC converters were meeting or exceeding their performance specification under all tested scenarios.

The Project demonstrated that an MVDC link can operate at different DC circuit voltages, between the design nominal of 27kV and minimum of 21kV. Within this voltage range, AC cables of varying ages and types, together with different overhead line sections, can be operated under a steady state and transient DC voltages without degrading the cable more than when operated under AC voltage.

Final acceptance tests, under full station power of 30MW, showed: MVDC link losses were under 3%, the cooling system performed as designed, the electromagnetic interference levels were below the maximum allowable values and the station noise levels exceeded those specified by the MVDC converter supplier. The noise level issue was mitigated using a sound enclosure.

Extended operational testing raised the system TRL. Following successful design, testing, installation and trial operation, the MVDC link TRL was raised from 6 to 8 and the technology is now ready for commercial deployment. The MVDC link is now operated under business as usual and is being used to reduce connection costs in 33kV connections applications.

Developers in Anglesey and North Wales are offered a connection, based on Angle-DC in operation which can release capacity at the point of connection. Often, connection applications require less or no network reinforcement due to Angle-DC. The need for a significant number of new wayleaves, for network reinforcement, has been avoided. The need for new wayleaves will continued to be reduced throughout RIIO ED2 and beyond.

2.4 OBJECTIVES MET

All the Project Successful Delivery Reward Criteria were met and are listed below.

- SDRC 1 Development of the Technical Specification for Holistic Circuit Condition Monitoring Systems.
- SDRC 2 Development of the Technical Specification for MVDC Converter Stations.
- SDRC 3 Commissioning of the Holistic Circuit Condition Monitoring Systems.
- SDRC 4 Factory Acceptance Test of MVDC Converters.
- SDRC 5 Installation of the MVDC Circuit.
- SDRC 6 Publication of Circuit Condition Data Report.
- SDRC 7 Operational Performance of the MVDC Converter Stations.
- SDRC 8 Successful Dissemination of Knowledge Generated.

2.5 KEY OUTPUTS AND MAIN LEARNING

Angle-DC has successfully demonstrated the capabilities offered by a Voltage Source Converter MVDC link and shown that the capital savings, losses and capacity benefits have been, and will continue to be, delivered throughout the lifetime of the installation. Angle-DC achieved the losses and capacity benefits through a combination of MVDC power control, fixed seasonal setpoints and remote operation. As the electricity system diversifies and evolves, the setpoints will be altered, based on network modelling and analysis, to maintain the losses benefits. An additional real time Local Control System has been developed and installed to operate the MVDC link setpoints under network intact and N-1 scenarios, without the need for control engineer intervention. The main outputs and key learning are detailed within this report and are summarised below.

Electromagnetic Compatibility The MVDC circuit runs on Britannia Bridge, adjacent to the rail deck. Network Rail viewed the AC to DC conversion as a change to the main-line railway, so the Common Safety Method was applicable under Office of Rail Regulations (ORR) document RGD-2013-06. Angle-DC was one of the first Projects to undertake a safety assessment, under this framework, so there was little or no precedence to draw from. To complete the safety assessment, the project required 7 separate organisations to provide studies and reports as evidence to show the risks were mitigated to an acceptable level. All the evidence required to support the conclusion, 'that the risk from operating the MVDC link, on NR infrastructure, is controlled to an acceptable level', was provided and accepted by Network Rail. Despite being complex and challenging, the outputs and learning from the first MVDC link Common Safety Method risk assessment, will be used to simplify and re-risk subsequent MVDC projects.

Cybersecurity

The MVDC link is an active, software controlled, device which needs to be actively managed to ensure the setpoints are optimal for the prevailing network conditions. The MVDC link requires network connectivity to allow remote operation and real time control. To provide network connectivity, new telecommunications infrastructure and cybersecurity safeguards were required within the MVDC converter, Local Control System and Telecomms network. These safeguards featured:

1. An air gap between the MVDC link control server and the real-time Local Control System using hardwired I/O;
2. Various communication protocol changes between the Local Control System and the Operational Data Network; and
3. The use of separate firewalled security zones that sit between the supplier remote access points and Angle-DC control servers.

The safeguards and security measures developed represented unique learning, which will be used for future network power electronic projects on the medium voltage network.

Transformer Noise

Standard tests under IEC 60076-10, do not provide accurate results for MVDC converter transformer noise levels, if the transformer currents contain a high harmonic content. The transformer housing should be designed as fully enclosed or the winding forces, due to harmonic currents, should be derived and 1/3 octave sound power levels guaranteed by the MVDC converter supplier.

Station Cooling

The cooling design of the MVDC converter station presented several design challenges. One challenge stemmed from uncertainty with the converter module heat output. MVDC converter suppliers should be challenged on their calculations, for module heat output, to avoid any oversizing the converter housing cooling system. Learning from the Angle-DC MVDC link valve hall heat output will be used to scrutinise design calculations of future power electronic projects.

3 Details of the Work Carried Out

The ANGLE-DC project was broken down into six distinct work packages, which enabled the ANGLE-DC solution to be delivered, while providing valuable learning to the UK electricity industry. A summary of the Work Packages (WP) is shown Figure 3-1 and will be discussed in this section.

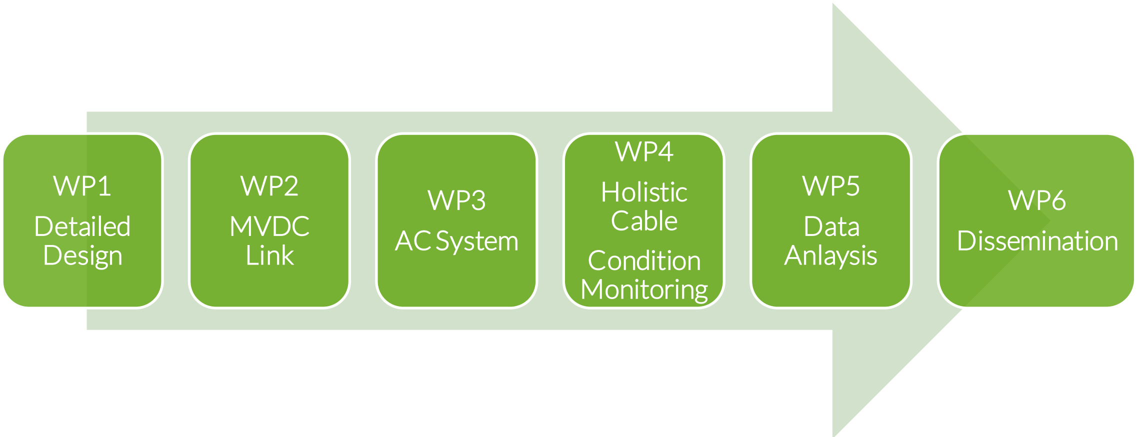


Figure 3-1. An Overview of the completed work packages in the Angle-DC project.

3.1 WORK PACKAGE 1 – DETAILED DESIGN

The main objective of Work Package 1 was to develop a technical specification for the MVDC link, including MVDC converters, interface transformers, control systems, compliance with engineering recommendations and station and network operating conditions. The functional specification, by its nature, did not presuppose choices of technologies or suppliers. Detailed system studies and a fresh review of MVDC technologies and supplier engagement were undertaken through a detailed supplier one to one process. SP Energy Networks also developed a detailed technical specification for real-time Partial Discharge (PD) monitoring of the DC circuit under this work package.

A thorough desktop study was completed, to develop an optimised power flow control strategy and set points of the MVDC converters under different generation and demand scenarios, which lead to the design speciation for the real time local control system, detailed in Section 3.1.3.

Appropriate design considerations were given to electromagnetic coupling (EMC) with Network Rail trackside assets such as the rail track, signalling systems and current and future train detection systems. This was achieved through the Common Safety Method Risk Assessment and Evaluation (CSM-REA) Process, detailed in Section 3.1.2. The output of this work was used to inform future MVDC link design requirements.

A protection scheme for the complete MVDC link developed with the MVDC converter supplier. The existing AC network protection system was integrated into the MVDC link protection system using relay and control signals from the transformer and MVDC converter control system. The protection concept is based on a series of overlapping protection zones from the existing AC networks through to the DC network.

3.1.1 Harmonic Loci Study

To aid the MVDC converter supplier design process, for harmonic performance on the AC side of the network, a network impedance study was carried out. This study consisted of deriving harmonic impedance loci, at identified critical bus bars for all N-1 operational scenarios in Anglesey and North Wales.

In addition to these studies, background harmonics (up to the 100th) were recorded before and during an outage of the Llanfair to Bangor Grid 33 kV circuit. This monitoring was required to capture the effect of separating the two networks and assess the level of background harmonics for each network. Both the Harmonic Loci results, and background harmonic data were used by suppliers to design any required AC side harmonic filters.

3.1.2 Common Safety Method - Risk Evaluation and Assessment

To allow real power transfer, DC current must flow in the converted MVDC circuit. The converted MVDC circuit runs over the lower decks of the Britannia Bridge, within the 'Railway Zone' as defined in the EMC and Network Rail Standards. When any technical or operational change is proposed, within the 'Railway Zone', a CSM-REA must be carried out. The conversion from AC to DC operation constituted a technical change to the railway.

Figure 3-2. Britannia Bridge lower deck showing the proximity of the Bangor to Llanfair AC circuit cables to the railway.

To carry out the CSM-REA, four safety organisations were appointed under the process: 1) The Proposer – Network Rail, 2) The EMC Modeller – Mott MacDonald, 3) The Safety Manager - Frazer Nash and 4) The Assessment Body – Ricardo Certification. The supplier used for each appointment was selected through a completive tender process.

The Safety Manager produced four safety reports: 1) The System Definition, 2) Hazard Identification and Record, 3) The Safety Plan and 4) The Safety Justification Report (SJR). The main inputs into the SJR were the EMC modelling results, which required DC fault scenario modelling results, from the MVDC converter supplier, as data inputs and a 3D model of every conducting material on the bridge.

Once the SJR was completed, the Assessment Body independently assessed the safety case documents and produced a Safety Assessment Report (SAR), which was presented to the Welsh Route System Review Panel in March 2021. The conclusion of the SAR was to permit energisation of the DC circuit, provided verification, through onsite monitoring, was carried out during commissioning of the real power transfer mode of the MVDC link. The verification and monitoring could only be done during a line blockage (a period with no commercial or maintenance trains running over Britannia Bridge), which could only take place between mid-night and 0600 on Sunday mornings. Five specialist teams were scheduled for the first DC link energisation:

1. Network Rail trackside induced voltage monitoring teams;
2. SP Energy Networks Senior Authorised Person and Senior Control Room Engineers;
3. A DC harmonic monitoring team;
4. GE on-site commissioning engineering teams; and
5. GE off-site control system specialists.

Due to the number of expert teams involved, significant levels of organisation were required, with SP Energy Network project managing the on and off-site coordination. The initial commissioning was completed successfully, on the first attempt, and provided all the evidence required to support the conclusion that the risk from operating the MVDC link, on NR infrastructure, is controlled to an acceptable level in accordance with CSM-REA.

3.1.3 Real Time Local Control System

The real time Local Control System (LCS) delivers one optimisation objective; minimum network losses, whilst satisfying N-1 outage conditions i.e., not causing thermal or voltage excursions, if outages were to occur within the Anglesey and north Wales network. This control system uses network measurements, local to the MVDC link, to calculate the converter real power set point in real time. Local network measurements are taken at boundary points, sitting between the 33kV and 400kV networks (grid sites), to capture the power flows between them. The Project installed monitoring equipment at four grid sites and establish local telecommunication to each grid site, by installing new telecoms equipment in various Anglesey and North Wales grid substations. This established a local monitoring network, which operates independently of any central telecoms network and wide area monitoring system. This improved the reliability of the LCS, because it can continue to operate if communications to the central control rooms are lost. The connectivity of the LCS network is shown in Figure 3-3.

The LCS detailed design required a desktop study, to establish if fixed seasonal setpoints could meet network operational requirements and release the losses for the benefits case, set out in the Angle-DC submission. Work was carried out by TNEI to study a Local Control System (LCS), which uses boundary monitoring at 4 grid sites to calculate real power transfer setpoints in real time. The study included for load and generation growth to the end of RIIO ED2. For certain combinations of generation and demand, the real power setpoint, using real time control, was closer to the optimum for losses reduction than using fixed seasonal setpoints. This is illustrated in Table 3-1 and Table 3-2. The real power setpoints, in these tables are derived from the real time control response curve in Figure 3-4.

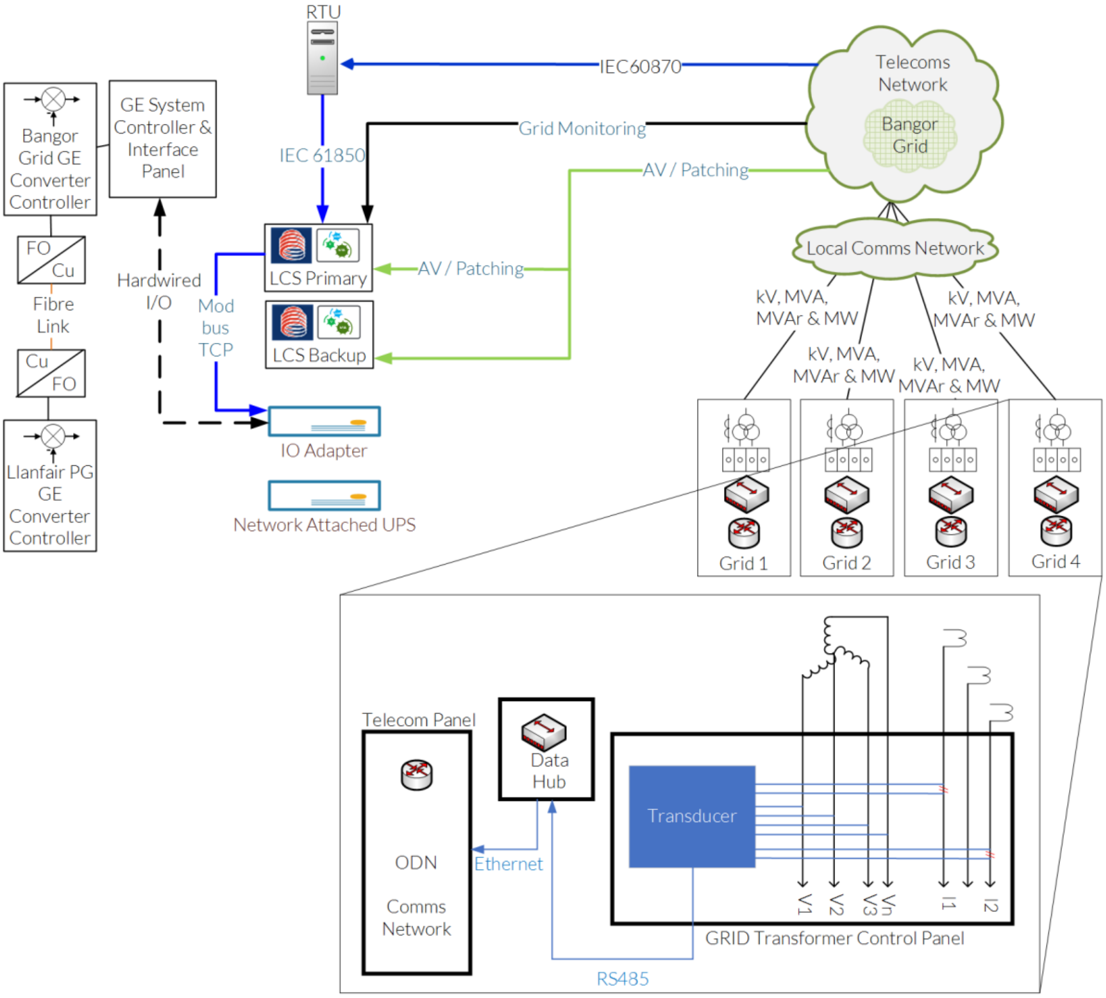


Figure 3-3. Angle-DC local control system connectivity diagram. Some details have been omitted for cybersecurity purposes.

Table 3-1 Difference between minimum network losses and losses at different MVDC real power setpoints, with 0% distributed generation. There is one table for each generation value. Blue boxes are the setpoint losses using LCS real time control, while the red boxes are the setpoint losses using fixed seasonal values.

		Δ Losses (MW)				
		SMIN	SMAX	WMAX	WMAX_x1.05	WMAX_x1.11
0%	25	0.687	0.554	0.087	0.089	0.030
0%	20	0.409	0.238	0.000	0.000	0.000
0%	15	0.165	0.102	0.088	0.067	0.091
0%	10	0.028	0.000	0.236	0.260	0.305
0%	5	0.000	0.059	0.510	0.630	0.631
0%	0	0.084	0.229	0.915	1.071	1.141
0%	-5	0.282	0.509	1.457	1.643	1.645
0%	-10	0.599	0.932	2.136	2.330	2.444
0%	-15	1.037	1.471	2.975	3.037	3.284
0%	-20	1.581	2.146	3.783	3.984	3.993
0%	-25	2.342	2.946	4.841	5.082	5.107

Table 3-2. Difference in real power setpoint for fixed seasonal setpoints (x) and real time setpoints (dot) for all load and generation scenarios. It can be seen the setpoints reach zero as the generation levels reach 100% generation.

	Generation: 0%					Generation: 25%					Generation: 50%					Generation: 75%					Generation: 100%				
	SMIN	SMAX	WMAX	WMAX_x1.05	WMAX_x1.11	SMIN	SMAX	WMAX	WMAX_x1.05	WMAX_x1.11	SMIN	SMAX	WMAX	WMAX_x1.05	WMAX_x1.11	SMIN	SMAX	WMAX	WMAX_x1.05	WMAX_x1.11	SMIN	SMAX	WMAX	WMAX_x1.05	WMAX_x1.11
25.00																									
20.00			•	•	•																				
15.00	•	•					•	•	•	•			•	•	•										
10.00			x			•		x					x					•	•	•			x		
5.00											•	•												•	•
0.00																•	•					•	•		
-5.00																					•				
-10.00	x	x				x	x				x	x				x	x				x	x			
-15.00																									
-20.00																									
-25.00																									

The LCS hardware was developed and tested by Nortech Energy Management LTD and then installed and site tested within the Bangor Grid substation, adjacent to the MVDC Converter hardwire IO interface panel. To support the LCS hardware operation, a new RTU, IO adapter, UPS and Human Machine Interface (HMI) were also installed, tested and commissioned. The LCS hardware was connected to the new telecoms network so that it could receive the local grid monitoring data and implement the real time control response curve setpoints to the MVDC converter control system.

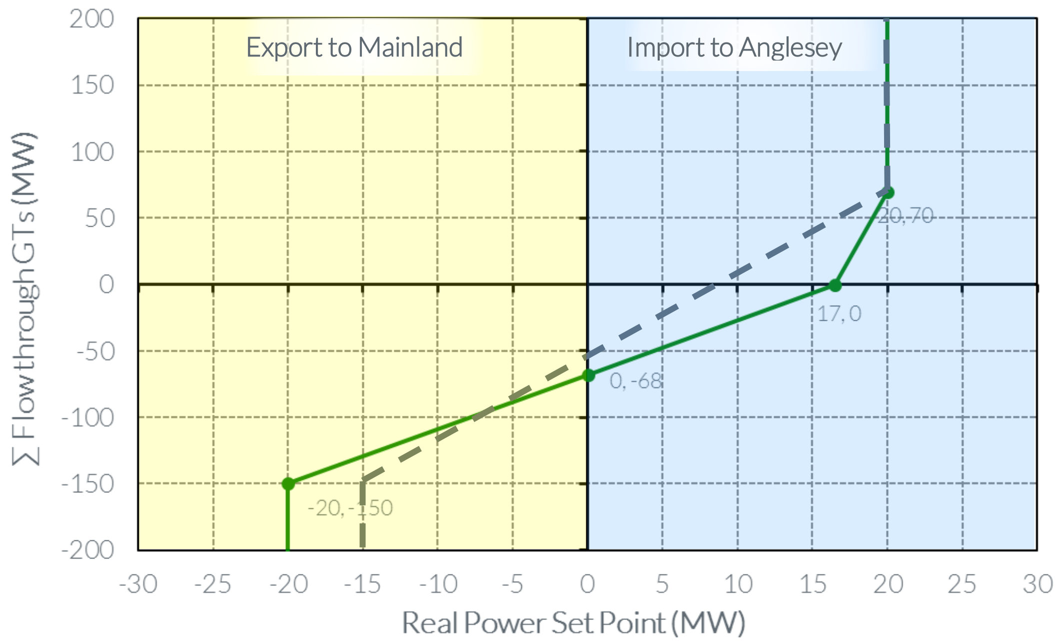


Figure 3-4 Real time control response curve, using net power import and export to and from Anglesey, for losses optimisation, system intact (dashed), and loses optimisation, with all N-1 operation constraints (green).

3.2 WORK PACKAGE 2 - MVDC LINK

Work package 3 includes all the activities required for manufacturing the equipment, site preparation, installation and commissioning the MVDC link. Based on the technical specification developed for the MVDC converters, SP Energy Networks selected four capable suppliers through a competitive tendering process. A summary of work carried out in work package 3 is listed below:

- MVDC equipment procurement;
- Factory acceptance test process;
- Site preparation at both Bangor and Llanfair PG substations, including civil and construction work, balance of plants a protection commissioning;
- Shipment of the equipment to the site;
- Installation of the equipment, site acceptance tests including equipment testing, cold and hot commissioning; and
- A converter station EMC study and verification through onsite measurement.

At the time of the project's delivery, there was no similar previous experience about procurement and installation of MVDC converters, in the UK, therefore significant learning for future MVDC applications was generated, which is detailed in Section 9.

3.2.1 MVDC Converter System Procurement

The MVDC Link was procured through an open and competitive tender process, which attracted global engagement from four manufacturers of medium voltage power electronic converters. A detailed technical specification was developed, for the MVDC Link, as part of Work Package 1 and SDRC 1. This was incorporated into the Invitation to Tender, which allowed prospective manufacturers to accurately tender for the contract to supply the MVDC Link. A thorough technical and commercial analysis of the tenders was carried out with leading power conversion experts, which led to the selection of GE Power Conversion to manufacture, install and commission the converter equipment within two purpose-built SP Energy Networks buildings. These buildings were built to the design specification provided by the MVDC converter supplier.

Following tender award, SPEN received a post tender specification, which contained additional building requirements, specifically: increased cooling loads, a positive pressure requirement and dew point control. These requirements would have to be met by using a HVAC system and a sealed building with a high build quality and tolerances.

3.2.2 Converter Station Buildings

The design of the converter stations buildings was primarily driven by the design of the MVDC converter system and component plant items. At tender, consideration of permitted development rights were incorporated into the MVDC converter specification to minimise the planning risk. Following engagement with the local community, building height and visual intrusion were cited as a major concern. The selected MVDC converter design had the lowest overall height profile, which kept the building height below 6m. The area taken by the building was specified to be no greater than ~ 20 x 20m. Due to the GE design not requiring AC filters, the final space requirements were 24 x 16m, within fully enclosed buildings.

The final building design used portal steel framework, enclosed by cavity brick and blockwork, covered in an insulated metal sheet roof. The whole building was supported by a concrete slab foundation, containing below ground pipe and cable trenches. The building envelope was made as compact as possible, to save on building costs. Other key consideration to the buildings design were as follows:

Diversion of existing cables – At Llanfair PG, existing cables ran within the proposed site and were diverted around the building footprint. Overhead line termination poles were also moved, to the substation site boundary, to make space for welfare facilities and the construction compound.

Installation of New Cables – Each site required the installation of new 33kV AC cables, to connect the bus sections to the converter 33kV transformers and connect the existing double 33kV circuit to the DC switchgear. Each site also required two new LV supplies, fed from different LV networks.

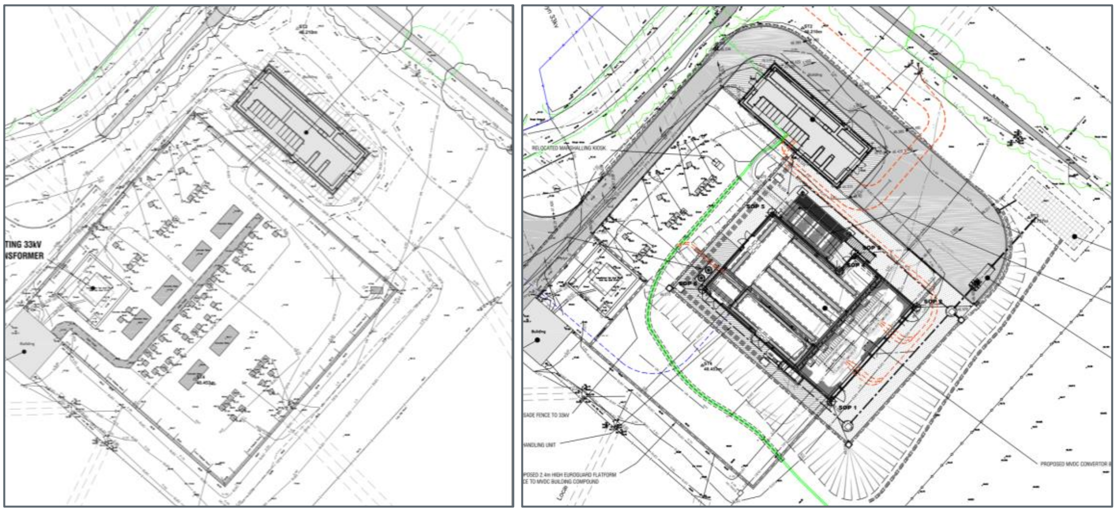
Flooding Risk – For both sites, the risk from rivers and sea were deemed low, whereas the surface flooding risk was deemed low with risk of increasing frequency and severity due to climate change affecting rainfall intensity. An oversized soakaway was installed at the Llanfair PG site to safeguard the site from future surface flooding.

Access for Installation of Plant- The sites were given a swept path analyse to determine the large plant items, namely the transformers, could be craned and slide onto their plinths, Factors such as road access, ground bearing capacity and distance from crane positions were considered.

Noise and Sound Propagation- The transformers were expected to be the greatest source of external noise, so these were enclosed within a transformer bay, which faced away from neighbouring domestic properties where possible.

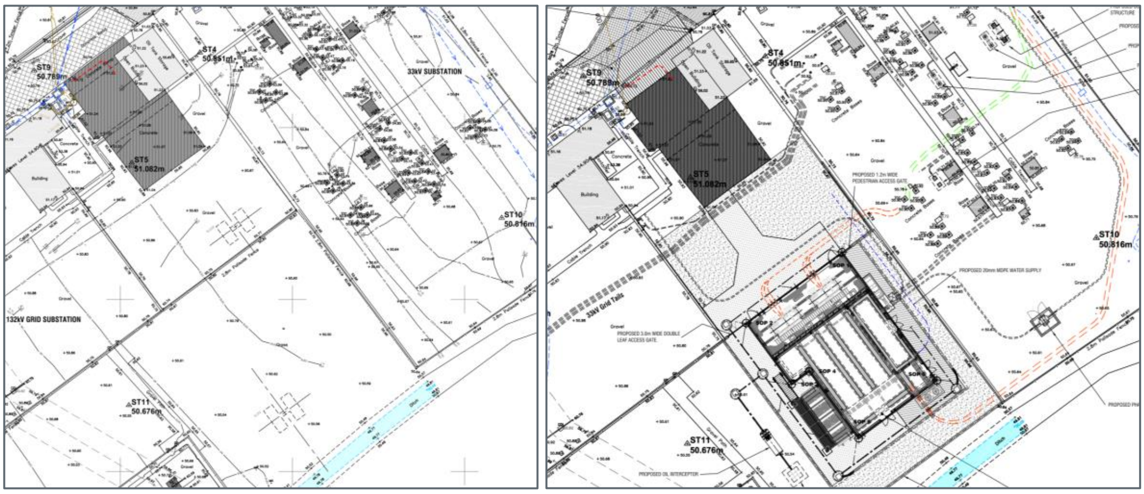
Following an initial tender, the final prices for the buildings were received from suppliers. The best prices received were almost double the value budgeted for the buildings. A proportion of cost rise came from the building environment HVAC system. Between July and September 2018, a considerable amount of effort was expended, by SP Energy Networks, to re-engineer the building design to bring the cost back to within the core budget and contingency. With the information available at the time, the Project believed protecting customer funding was of paramount importance and should take precedence over achieving the original project milestone dates.

The redesigned buildings were retendered, reducing the costs by ~30%. This released enough savings for customers to allow the project to continue within budget. However, this re-engineering, re-design and re-tendering pushed the building completion date back by 15-months. The buildings construction works began in early 2019 and were completed in late 2019. Figure 3-5 and Figure 3-6 show the 'before and after' site layouts for Llanfair PG and Bangor Grid substations respectively.



(a) *(b)*

Figure 3-5 (a) Llanfair PG original site layout. (b) Llanfair PG existing site layout with MVDC converter building showing diverted and newly installed cables.



(a) (b)

Figure 3-6 (a) Bangor Grid original site layout. (b) Bangor Grid existing site layout with MVDC converter building showing diverted cables.

3.2.3 MVDC Converter Station Plant Installation

The MVDC converter equipment was installed between January and July 2020. This included all balance of plant works (cabling, connections and cold commissioning) and plant installation. Physically, each station is separated into 5 main areas. Table 3-1 summarises the plant items housed in each area of the building, which are shown in Figure 3-7 and Figure 3-8. These areas are the: control room inverter valve hall, system cooling bay, DC switch room and a semi enclosed transformer bay.

The transformer bay houses two interface transformers, rated at 17 MVA which are of a unique design, with 1 HV and 6 LV windings, in a Y-d1d1d1d1d1d1 configuration. Each 3-phase winding has a 33/2.1kV voltage ratio and is connected to an inverter module with three 500 mm^2 XLPE AC cables, as shown in Figure 3-9. Therefore, there are 36 MV cables running from the transformer bay to the valve hall converter modules.

I n each station, the 12 converter modules are grouped into two groups of 6 independent single arm Neutral Point Clamped (NPC) converters, one group for each pole. Each group of 6 modules are interconnected in parallel on the AC side via the transformer LV windings. On the DC side, the 6 modules are connected in series to step up the voltage, in 4.5 kV steps, from 0V at the grounding point, to ± 27kV at the last module, which then connects to a DC reactor.

There are two DC reactors per station, one for each pole. These are air core reactors and have 6 mH of inductance, enough to reduce the fault current under the worst-case fault scenario. Each reactor is connected to a 630 mm^2 DC cable, which connects to the DC switchgear situated in the MVDC switch room.

The DC switchgear is a modified 3 phase AC air insulated panel, with the central phase removed. The switchgear comprises of two panels, one for the station side cable termination and the other for the circuit side cable termination. In the event of a permanent DC circuit fault, the converter station control system issues trip commands to the AC circuit breakers and opens the motorised 2-pole DC isolators (when the DC current decays to below 10A) and, after 3 hours, closes the motorised grounding switches when the DC link voltage has decayed to below 500V. The station's 2-pole isolators can only be reclosed by Authorised Personnel following rectification of a DC fault.

A detailed description of the installation process and connection works, for the MVDC converter stations, can be found in SDRC 5, "Installation of the MVDC Circuit Report". The report detailed the installation process of each piece of plant as well as key learning and recommendations for future projects.

Table 3-1. Summary of MVDC station plant items by building area.

BUILDING AREA	PLANT ITEMS
Control Room	Building dual LV supplies, GE LV converter power supply, the MVDC converter control system. Local Control Server and RTU and the interlocking panels.
DC switch room	DC switchgear
Inverter Valve Hall	12 off 3-phase Neutral Point Clamped Converter (NPC) converter modules, 2 off DC reactors, a Pre-charge unit and the AC and DC connections.
Transformer Bay	Two 33/2.1kV Y-dddddd Transformers.

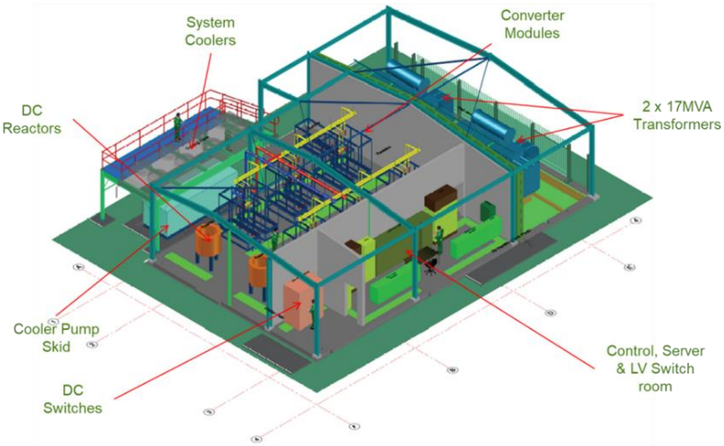


Figure 3-7 Detailed 3D General Arrangement of the MVDC stations with all plant installed.

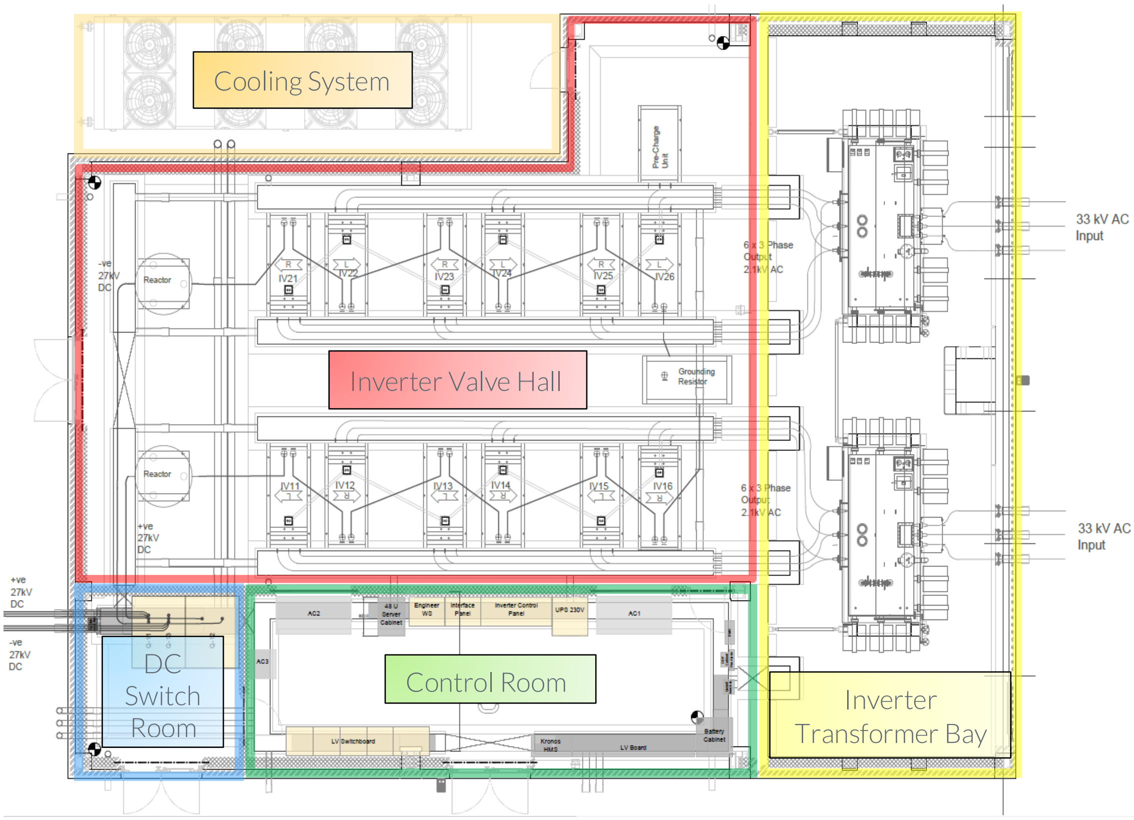


Figure 3-8. Physical layout of the plant items within each MVDC converter building.

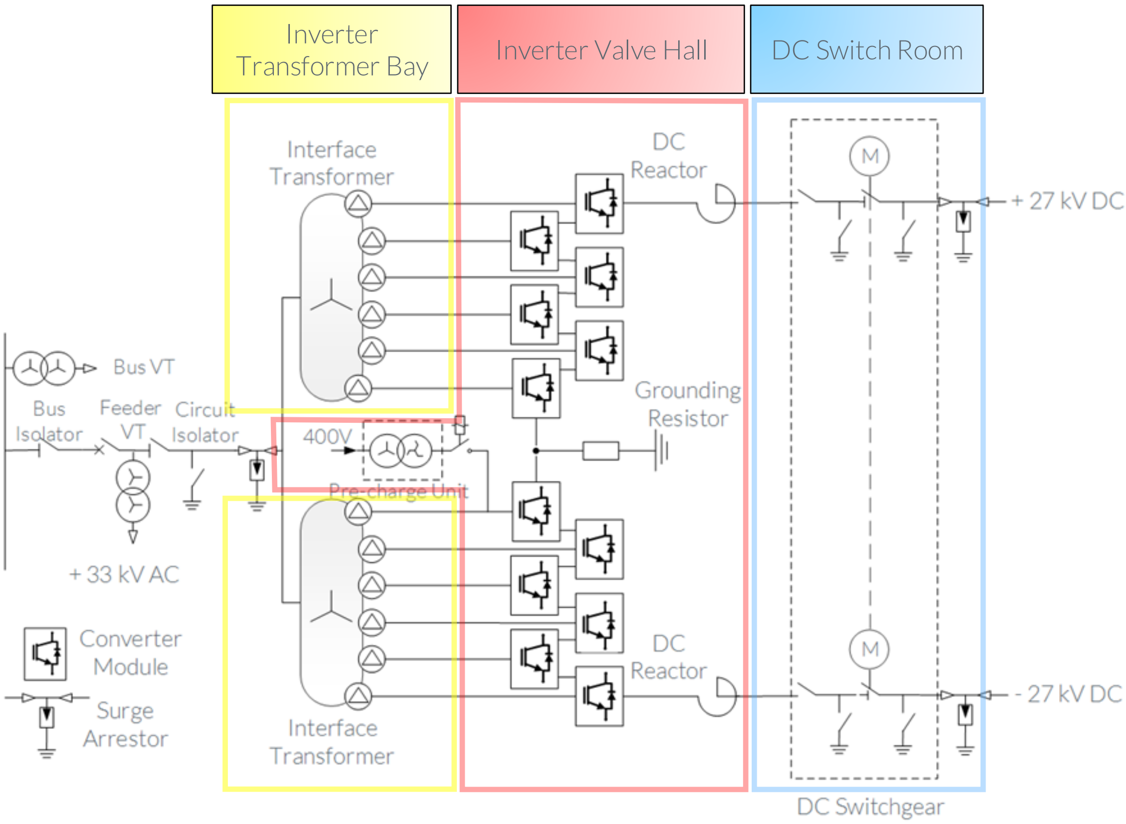


Figure 3-9. Electrical layout of one MVDC converter station developed for the Angle-DC project.

3.3 WORK PACKAGE 4- HOLISTIC CONDITION MONITORING

The circuit condition monitoring has formed an important learning outcome of the Angle-DC demonstrator project. The project has demonstrated a DC on-line PD monitoring system can be used to give an indication of present and 'trend in time' PD based degradation, which is caused by transient voltage stresses, including: voltage ramp up/down, over voltages and ripple from the power converters. The system also trended DC harmonics, detected from the converter switching, which can lead to electromagnetic interference at the converter stations and along the DC circuit. Data has been analysed and benchmarked to inform SP Energy Networks and other DNOs about the way in which distribution circuits age under DC stress. Pre and post-DC operation monitoring has allowed for validation of theories about how DC impacts on cable ageing.

The system that performed the condition monitoring was the Holistic Circuit Condition Monitoring System (HCCM). Delivery of the HCCM came in three parts: development of the technical specification (SDRC 1), installation and commissioning (SDRC 3) and cable condition data collection and analysis (SDRC5).

To achieve SDRC 1, the HCCM systems technical specification was shared with all UK DNOs, iDNOs and local Welsh 3rd party supplier networks via Welsh Assembly Government website 'Sell2Wales' in June 2016. The technical specification was also published on the Angle-DC Project website in June 2016. The specification contained the Scope and Objectives, Functionality, Architecture and Design of the HCCM system. This formed part of the Scope of Works for the procurement tender.

The procurement of the HCCM systems was completed in Q4 2016. The multicore duct enabling works and HV transducer installations at both ends were also completed during this period. The remaining. HCCM system equipment installation was completed in in Q1 2017, with the energisation of the Kronos cabinets and system server. The system began offline monitoring in January 2017 with HVPD collecting the first set of AC Partial Discharge results. A temporary GPRS modem was installed to allow online monitoring with Partial Discharge alarms.

A detailed description of the Holistic Cable Condition Monitoring (HCCM) system, installation process, connection works and preliminary monitoring results, can be found in SDRC 3, "Holistic Circuit Condition Monitoring System Report". The report details the installation process of each system component as well as the first set of AC circuit aging results.

In Q1 2018, substation cable diversions and relocation of the overhead line H-poles, into an adjacent field, was completed at Llanfair PG substation, in preparation for the building construction. The distant location of the new poles posed a difficulty in reconnecting the partial discharge sensors. As 12-months of AC cable trend data has already been collected, it was decided to avoid costly reconnection of the PD monitoring sensors. The Bangor Grid HCCM system continued monitoring until the building constructions works began.

Following the completion of the MVDC buildings and installation of the MVDC Link DC switchgear, in July 2020, the partial discharge monitoring equipment was re-commissioned. The Kronos cabinet and connection boxes were installed within the buildings. The Transient Earth Voltage Sensors, High Frequency Current Transformers (CT) and Power Quality CTs were installed within the cable panel of the DC switchgear. Following recommissioning, the partial discharge monitoring equipment, the harmonic voltage and current emissions and the real-time DC partial discharge trends, on the DC Link cables, were recorded. This enabled the analysis of the long-term partial discharge within the circuit cables under DC voltage which is detailed in Section 3.4.

3.4 WORK PACKAGE 5 - DATA ANALYSIS AND ENHANCED LEARNING

This work package was designed to build confidence in the MVDC technologies used in Angle-DC and capture the learning for the operation of the MVDC link. SP Energy Networks carried out several live tests on the performance of the MVDC link, including control of real and reactive power flows and DC and AC voltage. Details of these tests are described in Section 4.2. The withstand temperature of the cable circuits was also assessed by a gradually increasing in power through the cable circuit and monitoring the cable condition at the same time using the HCCM system.

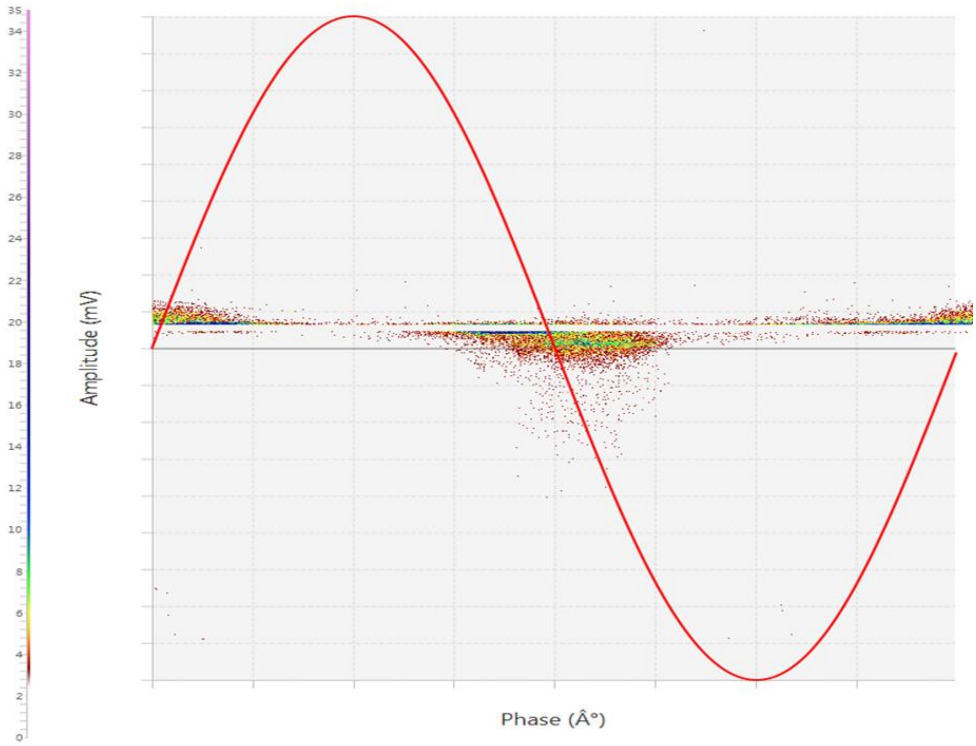


Figure 3-10 Phase resolved data from HCCM PD sensors, showing low levels of PD activity. The colour indicates the number of mV pulses that occurred at the recorded phase relative to the 50 Hz power cycle.

SP Energy Networks also prepared the technical installation guidance and policy documents for MVDC design and operation, which are detailed in Section 10.1. These documents are being used for preparation of the business case for the future and support "business as usual" MVDC applications.

3.5 WORK PACKAGE 6 - KNOWLEDGE DISSEMINATION

Significant learning was captured from the ANGLE-DC trial due to the innovative nature of the project. The Project deployed various methods of communicating the lessons learnt to other UK DNOs and the project's stakeholders during the project delivery phase and beyond. A full list of all dissemination activity is detailed in Section 12. The MVDC link is being retained for business-as-usual operation and dissemination will continue by making the data continuously available to interested parties.

4 Outcomes of the Project

The outcomes of the Angle-DC Project show that a fully operational MVDC Link can be deployed successfully on the 33kV distribution network, and they can be used it to manage power flows between a transmission and distribution network. The Method has shown that an MVDC link can reduce network losses and releases significant capacity on distribution networks, by balancing feeder loads, through real power control. Independent reactive power control has been demonstrated, at each end of the MVDC link, to optimise network voltage within a constantly changing network.

The architecture and system specification, required for implementing remote operation via a local control system, has also been developed, installed and commissioned, as well as the associated power system network modelling processes and systems integration that are used to calculate the MVDC link set-point curve. The MVDC converters and MVDC converter control system required factory acceptance tests before installation at site.

4.1 EQUIPMENT APPROVALS AND FACTORY ACCEPTANCE TESTING

Some elements of the MVDC system tests were based on standard items of passive network equipment. These are usually: AC disconnectors and breakers, line reactors, capacitor banks, transformers and AC and DC filters. The testing standards for these elements do not generally change because they are being applied to an MVDC application and the details can be found within the appropriate international and national standards. For the VSC modules, applicable MVDC testing standards come from either MV drive or VSC-HVDC applications, which are summarised in Table 4-1.

Table 4-1. Summary of applicable testing standards for MVDC factory acceptance testing. Note, not all clauses are applicable.

STANDARDS	TITLE
IEC 62501	Voltage Sourced converter (VSC) valves for high-voltage direct current (HVDC) power transmission – Electrical Testing
IEC 60060-1	High-voltage tests techniques – Part 1: General definitions and test requirements
IEC TR 62543	Performance of high voltage direct current (HVDC) systems with line commutated converters – Part 2: Faults and switching
IEC 61975	High-voltage direct current (HVDC) installations – System tests
IEC 60146-1-1	Semiconductor Converters
IEC 61800-4	Adjustable Speed Electrical Power Drive Systems – Part 4: General Requirements - Rating Specifications for AC Power Drive Systems above 1 000 V AC and not Exceeding 35 kV
IEC 61800-5-1	Adjustable Speed Electrical Power Drive Systems – Part 5-1: Safety requirements – Electrical, thermal and energy

(a) (b)

Figure 4-1.(a) Measured AC phase current and applied DC voltage during module load test (b) Photograph of the factory test set up for one VSC module.

4.2 DEMONSTRATION OF MVDC LINK CAPABILITY

The purpose of the initial commissioning was to test the MVDC link setpoint extremes and the control system dynamic stability. To achieve this, the setpoint schedule was split into three main parts: 1) low power steady state tests 2) high power transmission tests and 3) step response tests. The complete schedule can be visualised in Figure 4-2, which shows the real and reactive power recorded at the AC bus at Bangor Grid and Llanfair PG substations. Small differences in power, at each end, were observed, with the importing end always at higher real power than the exporting end. The difference is due to the converter switching losses. Although the converter station has a capacity of 33MVA, the nominal real and reactive power of the MVDC link is ±20MW and ±15MVAr. These nominal values were derived from the real time control studies and are implemented through control software limits, which can be raised and lowered as required.

While the commissioning was being carried out, key performance data was being collected to verify the findings of the CSM-REA and operational performance of the MVDC link. Four sets of monitoring systems were in place during the initial hot commissioning to collect the data:

- AC Feeder - Outram Power Master 7000 Power Quality Analyser;
- Converter Modules - The GE control system linked to the Pertu data historian;
- DC Circuit - A UNILYZER U900 DC cable power quality monitor and logger capable on monitoring up to the 100th harmonic; and
- Network Rail Track - The Network Rail data logger measuring rail to earth voltages and currents to 100,000 samples per second.

The initial commissioning monitoring results showed successful low power transmission tests for power flows in either direction. The high-power transmission tests were equally successful and were only limited by the amount of reactive power that could be imported at Llanfair PG due to the AC bus reaching voltage limits. The step change testing showed no issues, with the dynamic response of the converter control system to be critically damped following large setpoint changes of 10MW. The MVDC link also showed dynamic stability through a large voltage step change at Llanfair PG, when switching in an AC circuit. During the first two parts of the tests, several shutdown commands were issued, to observe the impact on DC cable harmonics and induced voltages during a fast ramp down of power.

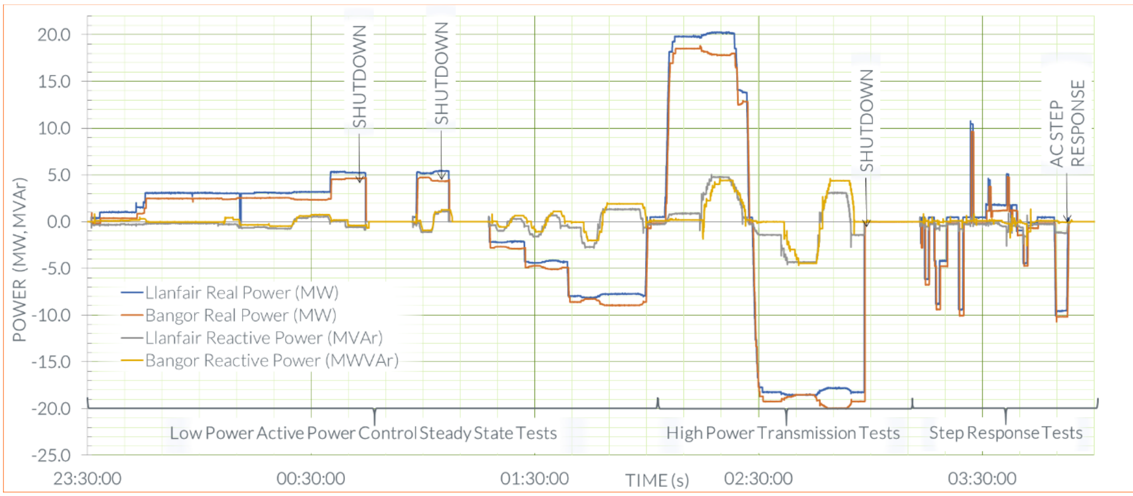


Figure 4-2. Initial hot commissioning test schedule showing real and reactive power setpoints achieved through the three main stages of testing.

During the commissioning period, the DC cable power quality monitors and Network Rail data logger recorded very low levels of harmonics and induced voltage in Network Rail track assets. These results confirmed the MVDC converters were meeting or exceeding their performance specification.

Following the initial commissioning, the MVDC link was operated for a 3-week acceptance testing period, in order to record key performance parameters, which are shown in Table 4-2. All the pass criteria were achieved, with the exception of the sound power levels at the nearest dwelling. The sound power pressure level achieved was ~40dB. This issue was resolved with an acoustic screen between the transformer bay and the nearest dwelling. This learning point is discussed in Section 9.3.

Table 4-2. Summary of MVDC converter acceptance tests.

DESCRIPTION	PASS CRITERIA	STATUS
Coolant temperature checks at full rated power (30MW);	< 43°C @ ~50m^3 / h.	Passed
MVDC link system losses at rated power	Station switching losses < 466 kW	Passed
Acoustic Monitoring over 2-weeks	<35db @ 73m.	Exceeded
Station EMC at rated power transfer, the field strength is </= 0.5/0.8mT	</= 0.5/0.8mT.	Passed
AC Network Harmonic Performance and compliance with ENA Engineering Recommendation G5/5	To comply with G5/5 based on background harmonic THD of 1.57%.	Passed
DC circuit harmonic performance	Below design levels.	Passed
AC voltage phase imbalance	<3%.	Passed
Loss of communications between stations	Station continues at current setpoint.	Passed

4.3 CHANGES TO THE TECHNOLOGY READINESS LEVEL

SP Energy Networks estimated a technology readiness level (TRL) of 5-6, at the project proposal stage, based on a literature survey and initial market engagement. At the module level, the winning MVDC converter supplier's solution was a mature technology, with over a decade of operation deployment as medium voltage drives and rail static frequency converters. At system level, the technology was less mature, with the system only tested as a 'hardware in the loop' (HIL) system at the factory, to test the

MVDC converter controllers. The HIL tests used ideal DC circuit and AC networks at each end, which leaves uncertainty regarding the interaction between the MVDC system and the AC network. The harmonic cancellation between the LV windings, in the transformers, was also only ever modelled, and not tested as a full system before installation at site. Therefore, the MVDC link, as a system, was only at TRL 6, as estimated at the proposal stage.

Extended commissioning testing was required to raise the system TRL, due to time being required to tune the converter modules under STATCOM commissioning. Due to the strong inductive coupling between all the modules, via the transformer LV windings, tuning the modules proved to be an iterative process. Following successful design, testing, installation and trial operation, the MVDC link TRL was raised from 6 to 8 and is now ready for commercial deployment. The MVDC link is now operated under business as usual and is being used to reduce connection costs in 33kV connections applications.

4.4 REDUCED WAYLEAVES

Within the SP Energy Networks planning and design department, Angle-DC is used as a connection solution during the design process. Developers in Anglesey and North Wales are provided a connection offer, based on Angle-DC in operation, which can release capacity at the point of connection. Often, connection applications require less or no network reinforcement due to Angle-DC. By increasing interconnector capacity, and increasing new AC network connections capacity, the need for a significant number of new wayleaves, for network reinforcement, has been avoided. The need for new wayleaves will continued to be reduced throughout RIIO ED2 and beyond.

5 Performance compared to the original Project aims, objectives and SDRC/Project Deliverables

The Angle-DC Project has delivered and performed over and above the requirements set in the SDRCs for most of the project. The Angle-DC project demonstrated an MVDC link can be developed, installed, commissioned and operated by UK DNOs proving it is a viable technology to be rolled-out in RIIO-ED2. The Angle-DC project is acknowledged internationally as a landmark project which created a roadmap for roll-out of MVDC links internationally for various utilities and vendors across the globe. A summary of each SDRC is given in Table 5-1.

Table 5-1. Summary of project performance against success criteria.

CRITERIA	EVIDENCE REQUIRED	OUTCOME	STATUS
SDRC 1 Development of the Technical Specification for Holistic Circuit Condition Monitoring systems.			
The Technical Specification will be published in the form of a document which will include a description of the Scope and Objectives, Functionality, Architecture and Design of the system.	Share the Technical Specification for the Holistic Circuit Condition Monitoring systems with other project stakeholders, principally other DNOs (17th of June 2017)	The Technical Specification for the HCCM system was shared with all relevant stakeholders on the 17th of June 2017. The technical specification was used in the tender for the HCCM system. The HCCM supply contract was awarded to program, allowing time for development and delivery of the HCCM system to meet SDRC 3.	Complete
SDRC 2 Development of the Technical Specification for MVDC Converter Stations.			
The Technical Specification will be published in the form of a document which will include a description of the scope and objectives, electrical specifications, control strategy and site installation requirements. This will also include the operating parameters for the scheme, which will be the subject to commercial guarantees.	Share the Technical Specification for MVDC converters with other project stakeholders, principally other DNOs (24th February 2017)	The Technical Specification for the MVDC converters was published on the Angle-DC website during February 2017. The technical specification was used in the tender for the MVDC converters. The MVDC converter supply contract was awarded to program, allowing time for development and delivery of the MVDC converters to meet SDRC 4.	Complete
SDRC 3 Commissioning of the Holistic Circuit Condition Monitoring Systems.			

CRITERIA	EVIDENCE REQUIRED	OUTCOME	STATUS
A report will be published in the form of a document describing the characteristics of the equipment installed, including the functionality and architecture and its integration into the SP Energy Networks monitoring systems. Photos of the devices at the sites will be provided as well as evidence of the data being recorded, and the trend information being stored.	Publish report demonstrating the on-site installation of the monitoring systems has been completed including photos of the devices at the sites and evidence that data is being recorded. Formal service support contract will be also signed with the supplier for analysis of the data (15 November 2017).	The installation and commissioning of the HCCM System was completed in Q1 2017 and data collection began at this time. A report describing the characteristics the Angle-DC HCCM system, including functionality, architecture and integration, was shared with stakeholders and uploaded to the website on the 15th of November 2017. The data gathered allowed the cable aging profile of the AC link, pre-conversion, to be determined. This provided confidence the circuit was in good condition, to allow DC conversion.	Complete
SDRC 4 Factory Acceptance Test of MVDC Converters.			
A report will be produced describing the testing procedure as well as findings from the testing.	Share report describing the testing procedure and highlighting the key findings during the Factory Acceptance Test (30 November 2018).	The project completed the FATS for the MVDC convertors ahead of schedule. The report was delivered on the 29th of November 2018. The FATs demonstrated the MVDC converter modules were fully tested before delivery to site, reducing the chance pf faulty parts or maloperation after installation. The testing reduced the risk of delay of SDRC 5 delivery.	Complete
SDRC 5 Installation of the MVDC Circuit.			

CRITERIA	EVIDENCE REQUIRED	OUTCOME	STATUS
A report will be produced and published in the form of a document describing the on-site installation of the MVDC converter stations process. The report will incorporate photos of the installed equipment and a description of the installation procedure.	Share report demonstrating the on-site installation of the DC circuit has been completed, including photos of the sites (10 July 2020). Share design of how the converters have been installed and key considerations for the future installations of MVDC converters (10 July 2020).	The installation of the MVDC circuit was completed in July 2020 by the MVDC converter supplier. The balance of plant and interface testing continued after this date, due to program inefficiencies caused by COVID. The installation of the MVDC circuit allowed commissioning tests to be concluded, before the MVDC link went into trial operation.	Complete
SDRC 6 Publication of Circuit Condition Data Report			
A report will be published on the project website summarising the data collected by the Holistic Circuit Condition Monitoring systems. The report will describe the condition of the circuit while in AC operation and how the condition changed, if at all, after conversion to DC. Data trending and conclusions will be presented.	Share report documenting the data gathered by the Holistic Circuit Condition Monitoring Systems. All incidences in the circuit since Holistic Cable Condition Monitoring system installation will be described, including the severity and mitigation measures (April 2021).	The HCCM is continually monitoring degradation data of the MVDC circuit under DC voltage. Periodic update reports are shared on the Angle-DC website to allow other DNOs to assess the suitability of converting their AC circuits to DC operation.	Complete
SDRC 7 Operational Performance of the MVDC Converter Stations			
A report will be published on the project website summarising the MVDC performance. The report will target the availability and reliability of the system. Outages rates and energy availability figures will be provided. A differentiation will be made between forced and planned outages. The report will include information on the maintenance regime, in terms of time and resources required.	Share the report documenting the performance of the system. The report will summarise the reliability and availability of the converters after the initial adjustment period. The report will differentiate between the forced outage rate (FOR), scheduled energy unavailability (SEU), forced energy unavailability (FEU) and energy availability (EA) (23 April 2021).	A verification and validation report was shared with stakeholders and published on the Angle-DC website. The report demonstrated the operational performance and reliability of the MVDC link. Evidence of the operational performance demonstrated that MVDC technology was successfully used within a UK distribution network.	Complete

CRITERIA	EVIDENCE REQUIRED	OUTCOME	STATUS
SDRC 8 Successful Dissemination of Knowledge Generated			
The knowledge and lessons learnt will be maintained in a knowledge repository where all learning points will be categorised based on their usefulness to different interested parties.	Timely delivery of project progress reports (by June and December of each year). Bi-annual knowledge dissemination workshops (bi-annual). Presentations at annual innovation conferences (Autumn 2016-2019, annually). Establishment and up-to-date maintenance of online project portal (ongoing). Publication of the close-down report (16 July 2021).	Each project progress report was completed on time, covering the original project duration. Where enough learning was gathered to share with stakeholders, Biannual workshops were completed to program. Presentations and papers where shared at internal conference several times each year.	Complete

6 Required Modifications to the Planned Approach During the Course of the Project

All project objectives and SDRCs have been met and the project has followed the planned approach in accordance with the original project proposal. Some minor changes are summarised in this section.

6.1 RELOCATIBILITY

The MVDC converter specification stipulated the complete MVDC installation should be capable of being re-located from the Llanfair PG and Bangor Grid sub-stations to other locations on the SP Energy Networks distribution network. It was anticipated that the power electronic converters, plus cooling, control, protection and auxiliary power equipment would be housed in a series of portable buildings., which, together with the transformers, should have been capable of being transported on normal freight vehicles, without the need for the special measures required for an "exceptional load". Only the cables between the converter stations would not be part of the relocation, along with some of the multicore, LV and communication wiring.

Following tender meetings, with four MVDC converter suppliers, this design consideration was given a low level of importance, when assessing the tender. This was due to the containerised solutions making less efficient use of the space and vertical height. For the Angle-DC project, height restrictions, due to planning considerations, were more important than relocating the stations, so this requirement was dropped from the MVDC converter design.

6.2 DETAILED DESIGN MODELLING

In the original project proposal, the MVDC converters were specified for unmanned operation, with either Pre-set power transfer levels, e.g., 100%, 80%, 60%, etc or Vernier control from full load to minimum power. The power ramp rate, between set points, was to be adjustable, but fixed as 0.5M/W per second, with a ramp rate being applicable to steps between pre-set power levels and to vernier control.

Due to cyber security safeguards (i.e., an air gap with hardwired I/O), the setpoint adjustments are performed through 'nudge control', which is performed by sending voltage pulses to the MVDC converter control system. Each pulse raises or lowers the set point by pre-set increment. To reduce the attention required by the control engineer, the number of nudges issued, to reach the desired setpoint, is performed by the control server. The sever monitors the setpoint value as a feedback, to ensure each setpoint nudge is received and implemented by the MVDC converter control system. The desired ramp rate is achieved by the duration of voltage pules.

6.3 TELECOMS REQUIREMENTS

The MVDC link is operated, via telecontrol, through the SP Energy Networks Operational Data Network (ODN), from a central control room. Certain high MVDC link setpoints can cause AC network thermal and voltage limits to be exceeded, at certain times, depending on the distribution of network load and generation. This is especially true during N-1 conditions brought about by forced (faults) and unforced (maintenance) outages. Using remote manual control, a loss of telecommunications, between the control room and the MVDC link, can lead to the MVDC link being stuck in a high-power setting, which risks circuits exceeding their ratings and bus voltages changing outside their limits.

To mitigate this risk, a local control system, uses local transducer data, allowing it to operate independently if communications with the central control room are lost. This control system requires a new local telecommunications network to be installed and commissioned. The function of the network is to transmit, local network connected, transducer data to the local control system, so the MVDC link setpoints can be automatically changed during communication loss with the control room. The creation of this new network required a robust operational cyber security assessment, to minimise the additional cybersecurity risk that comes with a telecommunications new network.

7 Significant Variance in Expected costs

Table 7-1. Summary of significance variance against total budget. Totals in millions GBP.

BUDGET CATEGORY	BUDGET (£M)	ACTUAL COST (£M)	VARIANCE (%)
Labour	1.815	[redacted]	[redacted]
Equipment	6.074	[redacted]	[redacted]
Contractors	5.366	[redacted]	[redacted]
Travel & Expenses	0.345	[redacted]	[redacted]
Contingency	1.200	[redacted]	[redacted]†
Other	0.040	[redacted]	[redacted]
TOTAL	14.839	[redacted]	[redacted]

Underspending areas are shown as a negative variance.

†The project has been delivered for a total value of £15.06M, representing a cost overrun of £221k that was absorbed by the business as additional commitment and to protect customer investment.

8 Updated Business Case and Lessons Learnt for the Method

This section will compare the proposed vs post project cost benefit analysis results (CBA). In the project proposal, the benefits were categorised into three areas to justify the Angle-DC business case. These were:

1. An interconnector capacity uplift of 5.7 MW and a net capital investment saving of £2.9M, when compared with conventional reinforcement used address the challenges facing the North Wales 33kV distribution network (detailed in Section 1.1).
2. Enhancing voltage and reactive power controllability, at both ends of the MVDC link and subsequently reducing losses by around 20%, which is equivalent to a saving per annum of £630k.
3. The roll-out phase replicating the ANGLE-DC solution at GB level will potentially result in total savings of £396.0m by 2050;

Since the scope of this close down report is the Angle-DC project, only the first two benefit categories will be assessed. The MVDC link has demonstrated a sustained power transfer of 30.5 MW during final acceptance testing. Therefore, the claim of an interconnector capacity uplift of 5.7 MW is a proven and justified benefit. The proposal capital cost of the MVDC equipment, which includes site preparation, was £8.1M. This value does not include budget for contingency. The Angle-DC MVDC equipment was delivered for £9.6M, a cost increase of £813k. This cost increase is accounted for by the increase in cost of the MVDC converter buildings and small increase in the MVDC converter system cost. The net capital savings are therefore reduced to £2.1M.

In the proposal, conventional losses of 65,703 MWh/annum were calculated under conventional reinforcement. With active power control, using and MVDC link with fixed seasonal setpoints, the proposal losses value (including MVDC link losses) was 52,673 MWh/annum, resulting in a losses reduction of 13,030 MWh/annum. SP Energy used 12-months' worth of pre COVID data, to verify the proposed network losses reduction.

9 Lessons Learnt for Future Innovation Projects

9.1 ELECTROMAGNETIC COMPATIBILITY

Potential Electromagnetic Compatibility (EMC) issues were understood before the project started i.e., Electromagnetic Interference (EMI) with railway telecoms and signalling equipment, since the double circuit cables ran parallel with the railway cables across Britannia Bridge. At the proposal stage, it was thought safety could be demonstrated by using DC filters at each station to eliminate DC cable harmonics. Following engagement with Network Rail, it was clear more detailed work to assess the EMI risk would be required. The Project engaged with Network Rail very early, through a joint Britannia Bridge site visit. From this visit, Network Rail viewed the AC to DC conversion as a change to the main-line railway, so the Common Safety Method Risk Evaluation and Assessment was applicable under Office of Rail Regulations (ORR) document RGD-2013-06. Angle-DC was one of the first projects to undertake a safety assessment, under this framework, so there was little or no precedence to draw from.

To complete the safety assessment, the project required 7 separate organisations to complete distinct work packages. Each of the organisation roles were procured through competitive tender and the interface between each was managed by the Project. The amount of modelling scenarios required was very large, and each needed to model the AC network and MVDC converter response up to 20kHz, which is four times the frequency of power quality standards like ER G5/5. The high frequency requirement was at the limits of traditional power flow modelling software. Once modelling challenges were overcome, the results were fed into several reports, which were assessed before going to Network Rail panel for review. Despite being complex and challenging, the learning from the first CSM-REA, for MVDC links, will be used to simplify and re-risk subsequent MVDC projects. All reports and modelling data will be made available to any follow up project upon request.

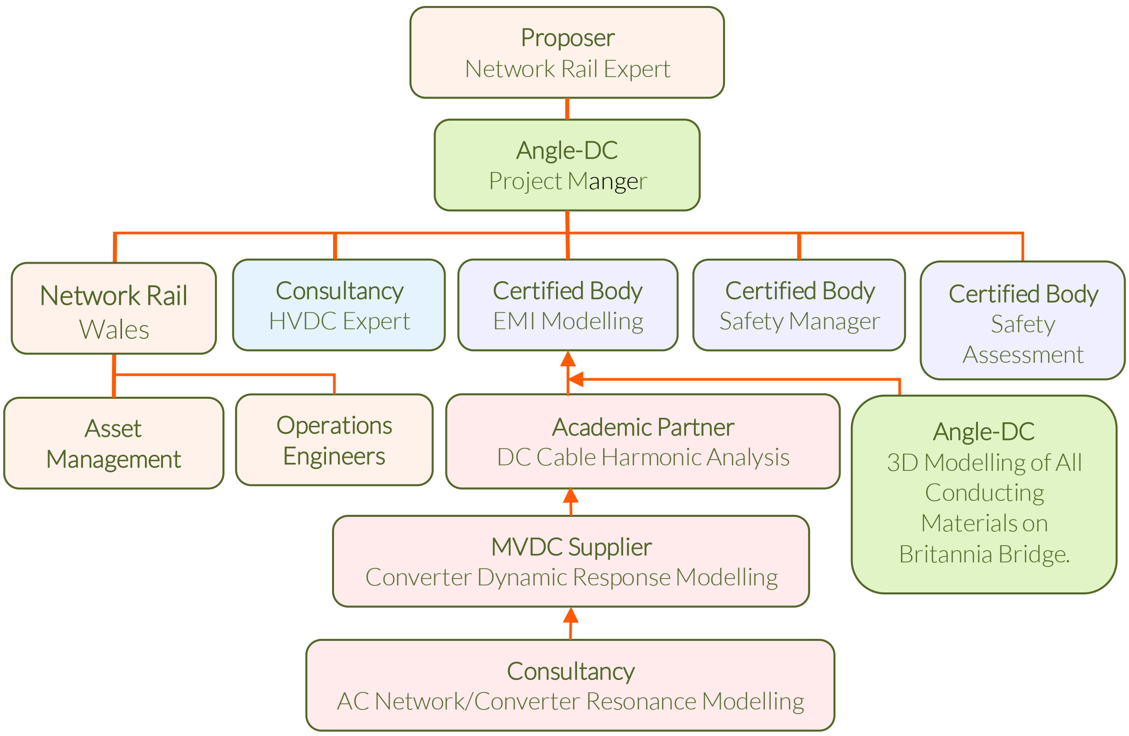


Figure 9-1 Common Safety Method safety case organisations.

9.2 CYBERSECURITY

The MVDC link is an active, software controlled, device. Because the hardware can be network connected, a cybersecurity risk exists. SP Energy Networks requires all suppliers to undergo a pre-contract cyber security questionnaire. Post contract, the final design undergoes another assessment before commissioning and then periodic assessments throughout the lifetime of the control equipment. The Angle-DC scheme has several cybersecurity safeguards built into its design:

1. An air gap between the MVDC link control server and the real-time LCS using hardwired I/O;
2. Various communication protocol changes between the LCS and the Operational Data Network (ODN) ; and
3. The use of separate firewalled security zones that sit between the MVDC converter and LCS supplier remote access points and Angle-DC control servers.

The safeguards and security measures developed represented unique learning, which will be used for future network power electronic projects on the medium voltage network.

9.3 TRANSFORMER NOISE

MVDC converter suppliers will have experience with converter modules but may not have commissioned a full MVDC link as a system, as this may be a new application for their technology. As a minimum, the supplier will estimate the transformer sound power level and, during factory acceptance, carry out sound monitoring in a walk around test, holding the microphone 1m for the transformer, when under full load. The standard spatially averaged sound pressure will be provided as a guaranteed sound pressure level.

The above is a standard test under IEC 60076-10, but this does not provide accurate results for MVDC converter transformers, if the transformer load currents have high harmonic content. Therefore, the transformer housing should be designed as fully enclosed or the winding forces, due to harmonic currents, should be derived and 1/3 octave sound power levels guaranteed by the MVDC converter supplier. If the guaranteed levels are exceeded, a contribution from the MVDC converter supplier should meet the cost of retrofitting an enclosure.

9.4 STATION COOLING

The cooling design of the MVDC converter station presented several design challenges. The first challenge stemmed from uncertainty with the converter module heat output. To deal with the uncertainty, the MVDC converter supplier overestimated the heat output value, to avoid insufficient cooling capacity once the station was built. The overestimation resulted in an oversized HVAC design, which increased capital costs. The Project scrutinised the heat output figure, provided by the MVDC converter supplier, who then relaxed the design specification for maximum room temperatures resulting in a lower calculated thermal heat output. This saved ~30% on HVDC capital cost. Further BaU savings on the HVAC system are possible now that the module heat outputs are known to be lower than supplier estimates.

The second challenge concerned deciding whether a closed or open HVAC system should be used. Most MVDC stations use open cooling systems, which rely of blowing large quantities of air through the valve hall from large, filtered louvres on the outside of the valve hall enclosure or building. The air flow transports heat to the outside of the building but requires large volumes of air to be pulled through the filters. This results in a high number of annual maintenance visits to change the filters (higher Opex). The closed system design requires more plant and pipework to be installed (higher Capex) but requires only one annual maintenance visit to ensure continuous operation. The trade-off between an open or closed HVAC system will need to be considered by any future MVDC link project.

9.5 SUMMARY OF LESSONS LEARNED

Table 9-1. Summary of Lessons Learnt for Future Projects.

OUTCOME	LESSON LEARNT	MITIGATING ACTIONS
Positive	The need for EMC analysis to understand the impact on 3rd party assets along the route of the DC circuit.	Ensure flexibility in the contract exists for the MVDC converter supplier to carry out multiple studies involving modelling 50 – 100 scenarios. Modelling must include AC and DC circuit electrical characteristics up to the twice the effective switching frequency of the MVDC stations.
Positive	Ensure cybersecurity safeguards are fit for purpose, in line policy and compliant with national standards.	Ensuring IT and cybersecurity personnel input into the development of system architecture and design, particularly in novel projects which can have 'unconventional' connectivity arrangements.
Negative	The importance of understanding the plant noise levels, across the sound spectrum, early in the design process.	Ensure transformer housing is designed as fully enclosed or the transformer winding forces, due to harmonic currents, are derived and 1/3 octave sound power levels guaranteed by the MVDC converter supplier.
Positive	The requirement to scrutinise supplier heat loss calculations so that the converter housing colling isn't overdesigned.	At tender suppliers should provide heat loss calculation and cooling system design, so this can be scrutinised by the procuring company.
Positive	Surface and river flooding risk assessments should be based on extreme weather.	The placement and drainage design of each MVDC station must consider rainfall extremes based on the most likely climate change emissions scenario. Surface level flooding can present a risk of water ingress into the converter housing. A raised design, for the converter housing and cable entry should be implemented even if this presents a planning risk due to height increases.

10 Project Replication

10.1 KNOWLEDGE REQUERIED FOR REPLIACTION

Three technical policy documents have been developed, which cover: 1) MVDC safety distances, 2) procedures for working safety within the MVDC converter building and on the MVDC circuit and 3) the functionality and control of the MVDC link. These documents are summarised in Table 10-1 and are available to other Network Licensees upon request.

Table 10-1List of technical policy documents developed under the Angle-DC Project.

REFERENCE	TITLE	ISSUE DATE
OPSAF-10-027	Work or Testing On or Near to High Voltage Direct Current (HVDC) Plant and Apparatus.	08/2020
OPSAF-11-107	Procedure for Working or Testing on the Angle-DC HVDC Link	12/2020
NMC-10-001	Angle DC System Functionality and Control	02/2021

10.2 BUSINESS AS USUAL COSTS

Replication of the Angle-DC project would incur significant cost savings against the original budget as future project will not require an AC back-up circuit and can use a containerised solution, which could release savings of up to 30% of the MVDC converter housing cost when compared with the Angle-DC buildings. Further BaU costs are described below.

10.2.1 Site Preparation and MVDC Converter Housing

The MVDC converter housing can either be within a standard substation brick building or a containerised solution. The containerised solution is likely to bring significant cost reductions, though was not offered at the time of tender by the MVDC converter supplier. The Angle-DC site preparation and building costs came in at £2.2M for both MVDC converter stations in 2018 prices. This figure included: site welfare facilitates, site supervision, enabling works, substation earthing, substation access roads, ground investigations, excavations, site drainage, MVDC converter cooling support structures and the building construction itself, including the HVAC system. The annual buildings maintenance cost is an average of £3,000/annum.

10.2.2 Spare Parts

Some spare parts are specialised and are not held in stock by the MVDC supplier. There will be a handful of long lead items that cannot be procured from the market, that will take up to 25 weeks to procure. Balancing losses benefit reduction due to prolonged outages, the capital cost reserved for spaces should be around 5% of the total contract price, every five years. This excludes the MVDC converter transformers, which have significant storage costs. The Network Licensee should calculate whether the benefit of having a transformer in strategic reserve, outweighs the capital and storage costs.

10.2.3 MVDC Converter Maintenance

Most of the MVDC converter maintenance could be covered by in house trained staff or by the MVDC converter supplier. On the Angle-DC project, the first year of maintenance was turnkey, with the supplier carrying out all maintenance activity. During the first year, SP Energy Networks maintenance staff will shadow all maintenance activity, to learn which maintenance tasks can be covered in house at reduced cost. The turnkey maintenance cost is approximately 1.6% of the MVDC Converter cost per annum. The converter stations will be shutdown up to 12 days per annum for maintenance. This annual outage will incur losses benefit reduction of around ~3.2%.

10.2.4 HVAC System Maintenance

For future projects, the HVAC system may be part of the MVDC converter contract. For the Angle-DC scheme, the HVAC system was procured separately from the MVDC converter at a cost of ~£320k in 2018 prices The maintenance cost associated with the plant come under £10k per annum for both stations.

10.2.5 LCS System Maintenance

The Local Control system will require regular inspection every 6 months to ensure the system cooling vents are clear of debris. The two severs require regular Anti-Virus and operating system patches as well as server license fees. When there is a significant network change, the LCS setpoint curve will need to be recalculated via a desktop study. This will ensure the MVDC link is optimised for losses through its 25-year lifetime. SP Energy Networks have estimated around £10k per annum for all the LCS maintenance activities discussed.

10.2.6 Staff Training

The Angle-DC project has developed a HVDC authorisation training course for: control engineers, senior authorised persons, overhead line field engineers, cable jointers and telecoms engineers. The training course is also available to external installation and maintenance contractors.

10.3 LIST OF PHYSICAL COMPONENTS

A list of all the MVDC link physical components are summarised in Table 10-2. The number of spare parts carried by the DNO should be considered, in order to reduce the MVDC link forced energy unavailability to a minimum, by minimising the lead time of replacement parts.

Table 10-2 MVDC link equipment required for project replication.

MVDC Link Item	Function	Description
MVDC Converter Control System	Provides switching timings to the Power Electronic switching devices.	This control system provides the switching timings to the Power Electronics based on the control loops for real and reactive power. The control scheme implemented is the background IP of the converter supplier. The control scheme directly affects the performance of the converter. The supplier must adhere to the performance declared at tender. The TRL of the control scheme must be 8 - 10, based on years of operational experience in similar applications.

MVDC Link Item	Function	Description
Real Time Local Control System	Provides real-time setpoint instruction to the MVDC Switching Control System.	This control system can use local or wide area monitoring data to calculate the MVDC link P and Q setpoints in real time, based on the chosen network optimisation objective. The setpoints will change with changing network conditions. Monitoring data should be polled every few minutes, to ensure the setpoints do not drift away from their optimum. The design of the control system will be different for each network application, though there will be common control system elements.
Converter Modules	Performs the switching action which controls AC and DC bus voltages and power flows.	The form of these modules will depend on the converter technology used by the supplier. The Angle-DC scheme employed Neutral Point Clamped Voltage Source Converters. Each model housed the control system, LV supply, cooling pipes and heat exchangers, IGBT stacks and 3.45 mF capacitor banks. The module house was an indoor open frame. The housing could have been an outdoor, fully dust and water sealed enclosure with its own IGBT and ambient cooling.
MVDC Converter Transformers	Cancels harmonics in the transformer secondary windings and steps the network voltage down to the converter module rated voltage.	The configuration of the transformers is dependent on the converter design. The Angle-DC scheme used two 33/2.1 kV Yd transformers with 6 secondary windings (one per pole). Each winding fed one converter module. The transformer used Oil Natural Air Natural cooling and are semi enclosed. Care should be taken with the acoustic design, since the transformers are the largest source of noise in each MVDC station.
Precharge System	Limits inrush current when connecting to the AC network.	Subsequent schemes can use pre-insertion resistors, or a pre-charge system. Both approaches limit the inrush current, to protect the AC network and DC power electronics, when connecting to the AC network. The Angle DC scheme used a 400V/2.1kV step up, star-delta transformer, with a motorised on-load isolator. A soft starter unit was used to reduce the LV in-rush current when energising the pre-charge transformer and converter DC capacitors.
DC Reactors	Limits the DC circuit fault current.	Some schemes may use DC reactors to reduce DC harmonic ripple and reduce the DC fault current. The reactor design, including inductive capacity of the DC reactor, is the responsibility of the MVDC converter supplier. The Angle-DC scheme used two 6 mH DC reactors, which were used as fault current limiting reactors only. The DC harmonics were cancelled using the transformer LV windings.

MVDC Link Item	Function	Description
LV Dual Supply and Changeover Switch	Provides LV supply redundancy.	Each station requires two LV supplies, two ensure continuous operation in the case a fault in the LV supply network. These supplies must be synchronised, so 400V / 400 phase shift transformers may be required.
MVDC Converter Cooling System	Directly cools the Power Electronic switches through indoor and outdoor heat exchangers.	The system comprises of a heat exchanger on each IGBT stack, a glycol/water cooling circuit, a pump skid, a water deioniser and an external heat exchanger with air forced cooling. The air forced cooling is provided by an array of fans, which require redundancy, since the MVDC converters can only operate for seconds without the cooling system.
HVAC System	Controls the air quality around the converter equipment.	The MVDC converter cooling system is designed to operate with a certain ambient temperature range. The HVAC system controls the ambient air temperature as well as maintenance the air quality including the relative humidity and dust ingress protection through filtration and positive pressure gradients.
DC Switchgear/Isolators	Electrically Isolates the converter stations	The DC switchgear can be offload, relying on the AC protection, or with a DC current breaking capability. The Angle DC scheme used an offload modified motorised AC disconnector. Because the disconnector has little current breaking capacity, the station capacitors must discharge below 500V before the disconnector can be operated. This takes up to one hour.
33kV Switchgear	Provides isolation and fault protection. Provides transducer data.	The 33kV switchgear makes and breaks the primary electrical connection between the MVDC converters and the AC network and protects the MVDC converters from faults. In the Angle-DC scheme, the switchgear provides AC feeder current and voltage and AC breaker states to the MVDC converter.
Protection Panels	Relays trip signal to circuit breakers. Lifts inhibit signal to MVDC Converter Control System.	In addition to standard feeder protection, new modular protection relays were required for the transformer protection signals and the signal confirming synchronisation between the MVDC converter feeder and AC bus voltage waveforms.
Interface Panel	Provides an interface between licensee and converter systems.	The interface panel provides an interface between the MVDC Converter Control server and the Local Control System servers and SCADA system. The Angle-DC interface consists of hardwired inputs and outputs which provide a cybersecurity air gap between the two systems.

MVDC Link Item	Function	Description
IEC60870 / IEC61850 RTUs	Relays MVDC inputs and outputs to Network Licensee systems.	The inputs and outputs include telecontrol commands, control feedbacks and alarms between the Network Licensee control room and the MVDC converter control system.

11 Planned Implementation

The MVDC Link, comprising of two converter stations, a converted DC bi-pole circuit and an AC protection scheme, has been fully commissioned to operational status. Operation of the converters show they have a wide area of power flow and voltage influence in Anglesey and North Wales. To operate as intended, the MVDC link required Anglesey network reinforcement works to be concluded, for the link to operate at its real/reactive power capability. These works were concluded before the end of the MVDC link commissioning, so no network modifications are required for the link to operate.

To operate within other networks, the real/reactive power capability needs to be sized correctly, to avoid over investment in an oversized MVDC link. Two main factors affect the optimal sizing of the MVDC link: 1) DC circuit capacity of the converted AC circuit 2) the ratings of the AC networks circuits either side of the MVDC link.

DC circuit capacity is dependent on the maximum current rating of the lowest rated cable type within the converted circuit. The rating will depend on a maximum allowable temperature of the cable insulation, which in turn will depend on many physical factors, such as cable type, duct type, daily load profile and depth of cable lay etc. The gain in current capacity from AC to DC conversion is usually ~2%, due to very little of the proximity and skin effects occurring within medium voltage DC circuits. Most of the AC to DC conversion uprating will therefore come from the DC voltage operating at the peak AC voltage, $P_{DC} \sim 1.41 P_{AC}$.

The ratings of the AC circuits, either side of the MVDC link, affect the optimal capacity of the link in a complex way. Network Licensees should carry out load flow studies, considering all combinations of the demand and generation, at each MVDC link setpoint for intact network conditions. The results from these studies will show what MVDC setpoints will violate thermal and voltage network for different network conditions. MVDC link ratings, that violate thermal and voltage constraints, under common network conditions, should be discounted.

To optimise the MVDC link capacity further, a real time control design could be completed before the MVDC link design specification is finalised, through an offline study. The real time response of the MVDC link could be assessed using half hourly SCADA data, to find the half hourly setpoint distribution. Setpoints not used could then be discounted, reducing the required MVDC link capacity. For example, the Angle-DC real power setpoint distribution can be seen in Figure 11-1, which shows a maximum of 22.5 MW. Some uplift of this maximum capacity is recommended to allow for future DER growth.

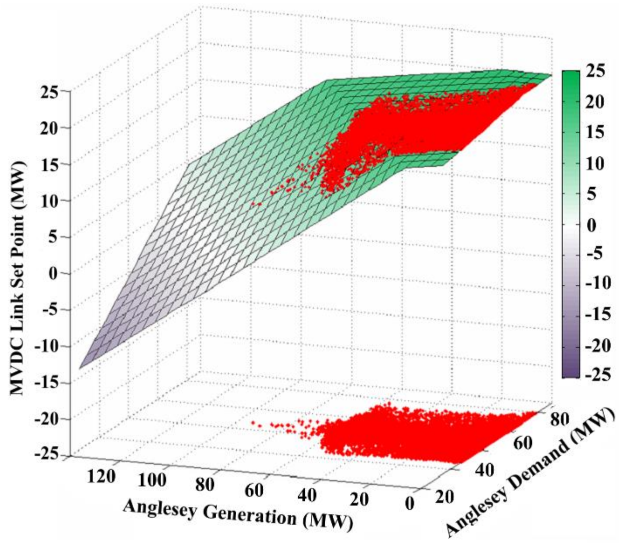


Figure 11-1. Real power point set point distribution on the control curve surface plot for the Angle-DC MVDC link when using hourly SCADA over two years.

12 Learning Dissemination

12.1 STAKEHOLDER ENGAGEMENT

The Angle-DC Project has continually shown a strong commitment to national and international stakeholder engagement. The Project has lead and participated in discussions with industry and sought out expert opinion to aid the delivery of project objectives. Key internal and external stakeholders were consulted throughout the project. The Project has sought out learning from other similar international projects to overcome key challenges. This has ensured that the project outputs satisfy the needs of key stakeholders, delivering maximum benefit from the Project.

Various formats were used for effective learning dissemination, which included:

- Posters at conferences (LCNI, CIRED, Cigré, ACDC and more);
- Presentations (individually led and at events / conferences);
- Publications on Various Websites (technical journals, conference proceedings, technical brochures and transactions);
- Steering Board Meetings (bi-annually);
- Webinars with UK DNOs and other stakeholders; and
- Workshops with UK DNOs and other stakeholders.

12.2 REPRESENTATION AT KEY INDUSTRY EVENTS

External stakeholder engagement activities have included attending and presenting at numerous recurring conferences including LCNI, Cigre, CIRED, IET HVDC international conferences, and the European Centre for Power Electronics. Presentation material from these events has also been made available to the wider audience through the conference websites.

Stakeholder engagement has been approached on an annual basis, in line with the annual cycle of many industry conferences and events. Stakeholder engagement has been planned at the beginning of each year in order to identify suitable activities and determine the content and representation at each event. A full timeline of the knowledge dissemination events attended or hosted is summarised in Table 12-1.

Table 12-1. Full list of learning dissemination activities by date.

EVENT TITLE	EVENT TYPE	FORMAT	DATE
ACDC 2017	Conference (International)	Paper and Presentation/Q&A to expert audience	February 2017
MVDC Technical Design	Internal Workshop	Speaker/Stakeholder Participation	February 2017
MVDC Technology and Supplier Engagement	Webinar	Speaker/Stakeholder Participation	April 2017
CIRED 2017	Conference (International)	Paper and Presentation/Q&A to expert audience	June 2017
International Conference on Applied Energy	Conference (International)	Paper and Presentation/Q&A to expert audience	August 2017

EVENT TITLE	EVENT TYPE	FORMAT	DATE
Cardiff University	PhD Colloquium	Keynote Speech	September 2017
Electronic Power Transmission and Distribution (IEEE eT&D)	Workshop	Paper and Presentation/Q&A to expert audience	November 2017
Energy Internet and Energy System Integration	Conference	Paper and Presentation/Q&A to expert audience	November 2017
Real-Time Circuit Condition Monitoring Systems for AC and DC Applications	Webinar	Speaker/Stakeholder Participation	November 2017
LCNI 2017	Conference	Presentation/Q&A	December 2017
Real-Time Circuit Condition Monitoring Systems for AC and DC Applications	External Workshop	Speaker/Stakeholder Participation	February 2018
Developments in Power System Protection	Conference (International)	Presentation/Q&A to expert audience	March 2018
European Centre for Power Electronics - DC Grids, Technologies and Applications'	External Workshop (international)	Presentation/Q&A to expert audience	April 2018
HVDC Operators Forum	External Workshop (international)	Presentation/Q&A to expert audience	June 2018
Cigré 2018	Conference (International)	Paper and Presentation/Q&A to expert audience	August 2018
ACDC 2019	Conference (International)	Paper and Presentation/Q&A to expert audience	February 2019
Innovative Smart Grid Technologies	Conference (International	Paper and Presentation/Q&A to expert audience	May 2019
LCNI 2019	Conference	Presentation/Q&A	October 2019
CIGRE Joint Working Group C6/B4.37	Webinar	Presentation/Q&A	September 2022

13 Key Project Learning Documents

13.1 PROJECT PROGRESS REPORTS

Progress report 1 – January 2016 to June 2016

Progress report 2 – July 2016 to December 2016

Progress report 3 – January 2017 to June 2017

Progress report 4 – July 2017 to December 2017

Progress report 5 – January 2018 to June 2018

Progress report 6 – June 2018 to June 2019

Progress report 7 – June 2019 to June 2020

13.2 PRESENTATIONS

TITLE	LOCATION	DATE
1st Angle DC Project Steering Group Meeting	SP Energy Networks Offices	June 2016
2nd Angle DC Project Steering Group Meeting	SP Energy Networks Offices	November 2016
Initial Designs for the ANGLE-DC Project; Converting Existing AC cable and Overhead Line into DC Operation.	13th IET International Conference on AC and DC Power Transmission	February 2017
Real time Control of a Distribution Connected MVDC Link (ANGLE-DC	13th IET International Conference on AC and DC Power Transmission	February 2017
3rd Angle DC Project Steering Group Meeting	SP Energy Networks Offices	June 2017
Initial Designs for the ANGLE-DC Project; Converting Existing AC cable and Overhead Line into DC Operation.	CIRED 2017	June 2017
Using an MVDC Link to Increase DG Hosting Capacity of a Distribution Network.	International Conference on Applied Energy	August 2017
The ANGLE DC Project and MVDC in Distribution Networks	Cardiff University- PhD Colloquium	September 2017
Operation and Control of Europe's First Bipolar MVDC link based on Neutral-Point Clamped Converters: An ANGLE DC Perspective	IEEE Workshop on Electronics Power Transmission and Distribution	November 2017
Real Time Circuit Condition Monitoring Systems for AC and DC Applications	Webinar	November 2017
Angle DC Project: The UK's first DC link using existing distribution network 33kV AC circuits	LCNI 2017	December 2017

TITLE	LOCATION	DATE
Real Time Circuit Condition Monitoring Systems for AC and DC Applications	Workshop	February 2018
Angle DC Project: Protection of Medium Voltage DC Links	Developments in Power System Protection	March 2018
Developments in the Angle-DC project: Project challenges, developments and findings to date	European Centre for Power Electronics	April 2018
Developments in the Angle-DC project: Project challenges, developments and findings to date	HVDC Operators Forum	June 2018
Developments in the Angle-DC project; conversion of a medium voltage AC cable and overhead line circuit to DC	CIGRE 2018	August 2018
Analysis of harmonic transfer through an MVDC link	15th IET International Conference on AC and DC Power Transmission	February 2019
Reliability evaluation of voltage source converters for MVDC applications	Innovative Smart Grid Technologies	May 2019
Dynamic Average Converter Model for MVDC Link Harmonic Analysis	13th IEEE PowerTech	June 2019
Steady-State Analysis on the Anglesey Network with MVDC Link. Dynamic and Reliability Analysis of MVDC converters on the Angle DC Link	LCNI 2019	October 2019
Comparisons of MVAC and MVDC systems in dynamic operation, fault protection and post-fault restoration	45th Annual Conference of the IEEE Industrial Electronics Society	October 2019

13.3 SDRC REPORTS

SDRC 1 – HCCM System Technical Specification

SDRC 2 – Medium Voltage Direct Current Link Technical Specification

SDRC 3 – Holistic Circuit Condition Monitoring - Report

SDRC 4 – Factory Acceptance Test of MVDC Converters - Report

SDRC 5 – Installation of the MVDC Circuit – Report

SDRC 6 – Circuit Condition Data – Report

SDRC 7 – Operational Performance of the MVDC Converter Stations – Verification and Validation Report

13.4 TECHNICAL PAPERS AND BROCHUERES

TITLE	PUBLICATION	DATE
Initial Designs for the ANGLE-DC Project; Converting Existing AC cable and Overhead Line into DC Operation.	13th IET International Conference on AC and DC Power Transmission (ACDC 2017), 2017, pp. 1-6.	May 2017

TITLE	PUBLICATION	DATE
Real time Control of a Distribution Connected MVDC Link (ANGLE-DC).	13th IET International Conference on AC and DC Power Transmission (ACDC 2017), 2017, pp. 1-6.	May 2017
MVDC Link in a 33 kV Distribution Network.	CIRED - Open Access Proceedings Journal 2017(1):12-15	June 2017
Operation and Performance of a Medium-Voltage DC link	CIRED - Open Access Proceedings Journal 2017(1):1355-1358	October 2017
Developments in the Angle-DC Project; Conversion of a Medium Voltage AC Cable and Overhead Line Circuit to DC.	Study Committee B4, 2018 2018 Session Papers and Proceedings B4-202_2018	2018
Using an MVDC Link to Increase DG Hosting Capacity of a Distribution Network.	Energy Procedia Volume 142, Pages 2224-2229	December 2017
Dynamic control of MVDC link embedded in distribution network: — Case study on ANGLE-DC.	2017 IEEE Conference on Energy Internet and Energy System Integration (EI2), 2017, pp. 1-6	January 2018
Reliability Evaluation of Voltage Source Converters for MVDC Applications.	2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)	October 2019
Analysis and Protection of Converter-Side AC Faults in a Cascaded Converter-Based MVDC Link: ANGLE-DC Project.	IEEE Transactions on Smart Grid, pp. 1-1	December 2021
Medium Voltage DC Distribution Systems.	Study Committee, C6/B4, Joint Working Group C6/B4.37 Technical Brochure 875	May 2022

A selection of the technical papers has been collated into a single document which is available for download on the Angle-DC website.

14 Data Access Details

To access and download material generated through the project, please visit the Angle-DC website using the link below:

https://www.spenergynetworks.co.uk/pages/angle_dc.aspx

For more information regarding the Angle-DC project, please contact Andrew Moon or James Yu, Future Networks Manager, SP Energy Networks.

15 Material Change Information

One significant learning outcome came from talks with suppliers, who stated a relocatable link would be unfeasible. Therefore, a fixed installation was selected and designed for. Following tender award, SPEN received a post tender specification, from the selected supplier, which contained changes, specifically: increased cooling loads, a positive pressure requirement and dew point control. These requirements would have to be met by using an expensive HVAC system and a sealed building with a high build quality and tolerances.

In late June 2018, the final prices for the buildings were received from suppliers. The best prices received were almost double the value budgeted for the buildings. A proportion of the cost rise came from the HVAC system. Between July and September 2018, a considerable amount of effort was put in by SP Energy Networks to re-engineer the building design to bring the cost back to within the core budget and contingency. With the information available at the time, the Project and review board believed protecting customer funding was of paramount importance and should take precedence over achieving the original project milestone dates.

The redesigned buildings were retendered to suppliers, reducing the costs by ~30%. This released enough savings for the customer and to continue the project within budget. However, this re-engineering, re-design and re-tendering pushed the building completion date back to Q4 2019. This has led to between a 12 to 15-month delay to the project and delay claims by the MVDC converter supplier. These claims have been managed by the Project.

The buildings construction works began in February 2019 and were completed in Q4 2019. MVDC installation took place between Q1 2020 and concluded in July 2020. These dates, which matched the estimates given in the material change request, moved each subsequent milestone date back 15-months. Two of the major milestones, which were moved, were the installations of the MVDC and backup AC circuits, which affected the SDRC report publication dates, because these reports required data from the operation of the MVDC link.

15.1 SUMMARY OF MATERIAL CHANGE REQUEST

The material change requests are summarised in Table 15-1, as a 15-month time extension for SDRCs 5 – 8 and the final project completion date.

Table 15-1. Summary of material change request.

ITEM	ORIGINAL DATE	NEW DATE
SDRC 5 Installation of the MVDC circuit	12/04/2019	10/07/2020
SDRC 6 Publication of circuit condition data report	23/01/2020	23/04/2021
SDRC 7 Publication of operational performance of MVDC converter stations	23/01/2020	23/04/2021
SDRC 8 Successful dissemination of knowledge generated	16/04/2020	16/07/2021
Project Completion	16/04/2020	16/07/2021

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