Angle-DC

SDR Application

About Report

Report Title	:	**Angle-DC Successful Delivery Reward Application**
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Acronyms

DNO	Distribution Network Operator
EMI	Electromagnetic Interference
HCCM	Holistic Circuit Condition Monitoring
HVDC	High Voltage Direct Current
MVAC	Medium Voltage Alternating Current
MVDC	Medium Voltage Direct Current
NIC	Network Innovation Competition
OHL	Overhead Line
PD	Partial Discharge
SDRC	Successful Delivery Reward Criterion/Criteria
SPEN	SP Energy Networks

Executive Summary

Approved under Ofgem's 2015 Network Innovation Competition (NIC) mechanism (and modified in 2020), the £14.8m Angle-DC project has been a national energy innovation flagship project. SP Energy Networks (SPEN) 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 flagship Angle-DC Network Innovation Competition (NIC) project has been a successful project in a technical, economic, social, and academic sense. It successfully delivered technical and economic benefits and contributed to the transition towards net zero. The project sets out to demonstrate both the technical feasibility and the commercial viability of converting an existing MVAC circuit (in this case an AC distribution OHL and cable) to an MVDC circuit. By installing Power Electronic technology, this conversion from AC to DC has been demonstrated both the ability to efficiently increase network capacity to accommodate renewable energy growth and to offer other system benefits e.g. local voltage control capability. The project itself has delivered a network upgrade at a lower cost than the business-as-usual approach with significant savings. The total saving for this project compared with the business-as-usual approach is estimated at £2.1 million, with a further annual saving of c. £630k/annum due to the voltage control capability and lower electrical losses along the DC circuit (compared to AC operation). The solution could also enable further savings of circa £400 million in infrastructure upgrades if AC to DC conversion on targeted medium voltage circuits is rolled out nationwide by 2050, providing excellent "value for money" in innovation investment for consumers. Innovation such as this plays a critical role in enabling a fair, low carbon energy transformation, and the potential capacity uplift from the conversion benefits renewable resources connection into the grid.

The active power flow control that ANGLE-DC has trialled helps to future-proof the network against the inherent uncertainty of future generation and demand growth. Angle-DC has also reduced costs to the consumer through reduction of losses and more cost-effective network capacity increase as follows:

- Losses optimisation – providing control room operators with calculated seasonal and real time reference setpoints, to help reduce network losses, even as the distribution of load and 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.

Beyond the proof of benefit and the direct savings, the project has laid fundamental groundwork for future projects of a similar design to build upon. As part of the Successful Delivery Reward Criteria (SDRC), the project has developed specifications including those for the Holistic Circuit Condition Monitoring (HCCM) System and for MVDC converter stations. The knowledge and learning gained from the project have been collated and disseminated into the development of relevant international standards and papers, including successful publication of CIGRE Technical Brochure (TB 875) "MVDC Distribution Systems" by Joint Working Group JWG C6/B4.37. This learning has been a particular success from the project, exceeding initial expectations.

There were some challenges in delivery due to the "first of its kind" nature of the project. The converter station building costs were higher than initially forecast. Also, additional EMI tests were required due to the location of the project and there were unexpected issues with cooling requirements for the converters and transformer noise. These were effectively mitigated where possible through robust project management and engineering approaches. The learning from these issues has been shared with industry via project reports and publications, to enable future MVDC projects to achieve higher cost effectiveness and a better value for customers.

The Angle-DC project commenced in January 2016, with an initial completion date of April 2022. A 15-month extension was later approved by Ofgem, to allow further time for the converter station building redesign and to enable the finalisation of the operational data capture and analysis scheme.

This document constitutes the application by SPEN for a successful delivery reward for the Angle-DC project, with all SDRC successfully delivered despite the challenges, particularly during the Covid-19 period.

1. Successful Delivery Award Criteria

1.1. Overview

The Successful Delivery Reward Criteria were introduced in the original Project Direction document for the Angle-DC project as released by Ofgem. Our performance against the SDRC is summarised in Table 1.

All SDRC for the project were delivered successfully, despite significant levels of disruption due to the Covid-19 pandemic and unexpected costs. However, through effective project management and with a project guidance alteration allowing an extension of time for some SDRC, the project was completed to a very high standard of technical delivery, cost efficiency, information dissemination and customer benefit. Further details are summarised below from the details in the corresponding evidence, i.e. the Angle-DC Project Close Down Report, project progress reports, and other relevant documents listed in Appendix. All documents and reports cited in Table 1 are available upon request.

Table 1: Summary of SDRC Performance

SDRC	Criterion and Required Evidence	Status and Comments
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.	**Complete.**
	Share the Technical Specification for the Holistic Circuit Condition Monitoring systems with other project stakeholders, principally other DNOs (17 June 2016).	
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.	**Complete.**
	Share the Technical Specification for MVDC converters with other project stakeholders, principally other DNOs (24 February 2017).	
SDRC 3: **Commissioning of the Holistic Circuit Condition Monitoring Systems.**	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.	**Complete.**
	Publish report demonstrating the onsite 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).	
SDRC 4: **Factory Acceptance Test of MVDC converters.**	A report will be produced describing the testing procedure as well as findings from the testing.	**Complete.**
	Share report describing the testing procedure and highlighting the key findings during the Factory Acceptance Test (30 November 2018).	
SDRC 5: **Installation of the MVDC circuit.**	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.	**Complete.** **Additional Comments:** By the end of July 2020.
	Share report demonstrating the on-site installation of the DC circuit has been completed, including photos of the sites (Originally 12 April 2019 change request granted to **10 July 2020**). Share design of how the converters have been installed and key considerations for the future installations of MVDC converters (Originally 12 April 2019 change request granted to **10 July 2020**).	
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.	**Complete.** **Additional Comments:** Complete by the extended deadline.
	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 (Originally 23 January 2020 change request granted to **23 April 2021**).	
SDRC 7: **Publication of operational performance of 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.	**Complete.** **Additional Comments:** Operational performance was published in a report, however the period between the commissioning of the converter stations (July 2020) and the extended deadline (April 2021), was not sufficient to gather
	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) (Originally 23 January 2020 change request granted to **23 April 2021**).	meaningful outages rates and energy availability figures. SPEN will publish any unplanned outage and unavailability data outside of the 2 weeks annual maintenance on its innovation website, following 5 years of operation.
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. (Originally 16 April 2020 change request granted to **16 July 2021**).	**Complete.** **Additional Comments:** Complete by the extended deadline.

1.2. SDRC 1 – Development of the Technical Specification for a Holistic Circuit Condition Monitoring Systems

Criterion

The aim of this SDRC was to successfully deliver a technical specification for a Holistic Circuit Condition Monitoring System, in the form of a document including a full description of the scope, the objectives, the functionality, architecture and design of the system.

Performance

The requirements for this SDRC were met in the production of the SDRC Document 1 "**NIC Project Holistic Circuit Condition Monitoring Specification**". This document provided in detail the functionality and measurement requirements in addition to location, maintenance, and warranty requirements. The document can be found on the ANGLE-DC website as "HCCM System Technical Specification".

The HCCM System was able to conduct real time monitoring of live circuits either AC at 33kV, or up to ±27kV DC. For AC monitoring, the HCCM System provided the footprint of Partial Discharge (PD), Transient Earth Fault detection, transient overvoltage detection, Power Quality monitoring, and OHL and underground cable temperatures. For DC monitoring, it provided all measurements for AC, plus the DC converter ripple measurement.

This document was shared and reviewed on time by the 17 June 2016 within its allocated deadline. The primary audience for this document, and those who would most benefit from the learning from this project, were the other DNOs in GB.

1.3. SDRC 2 – Development of the Technical Specification for MVDC Converter Stations

Criterion

For this criterion, a technical specification had to be published which would cover aspects of an MVDC converter station from scope and objectives through to operating parameters. This was to be shared with other project stakeholders, principally other GB DNOs.

Performance

SPEN has successfully achieved this SDRC. A detailed technical specification was produced which enabled the successful build of two MVDC converter stations. The **'NIC Project Medium Voltage Direct Current Link Technical Specification'** report was delivered on time and shared with the relevant stakeholders. One of the main benefits of the publication was that it would allow for speedier adoption of the technology across the GB distribution system as this specification had been put into practice and resulted in a successfully delivered project.

The document can be found on the ANGLE-DC website as "MVDC Link System Technical Specification". In this report, the scope and objectives were clearly introduced. Electrical specifications including power rating, DC voltage rating, voltage reduction capability to clear a transient fault etc, were discussed. Control of the MVDC circuit was covered in Chapter 11 on a high level. In addition, requirements of operating temperature, noise level, reliability and availability, operating losses, harmonics, auxiliary power and network dynamic performance were specified.

A technical specification was developed and shared with the relevant stakeholders within the allocated deadline, in addition to which, a CIGRE Technical Brochure TB875 (from Working Group C6/B4.37) Medium Voltage Distribution Systems, was developed and published. This brochure detailed not only the performance requirements for the converter stations but also other components of the full MVDC System.

Development of internationally recognised standards pushes forward the roll-out of technologies such as MVDC by giving other DNOs or developers the confidence in a technology where the approach and methodology have been internationally recognised. Angle-DC provided a clearer pathway to further development of the technology and as such SPEN has gone beyond the original remit in pushing innovation from trial projects to business-as-usual roll-out, not just within SPEN but across the GB network. This criterion was achieved within the required deadline of the 24 February 2017 with the development and publication of the Technical Specifications.

1.4. SDRC 3 – Commissioning of the Holistic Circuit Condition Monitoring Systems

Criteria

The aim for this criterion was to produce a document describing the characteristics of the equipment installed, detailing the functionality and architecture and how it was successfully integrated into the SPEN monitoring system.

Performance

This criterion was successfully achieved within the required deadline of the 15 November 2017 with the publication of the report '**Holistic Circuit Condition Monitoring System Report'**. The document can be found on the ANGLE-DC website as "HCCM_Systems_v1.01".

The Holistic Circuit Condition Monitoring system has exceeded expectations in its performance. It was successfully installed and commissioned, and the benefits have been seen in the range of measurements that it has been possible to take and the approach which has led to higher accuracy in determining the status of the cable than alternatives might have.

The system is formed of HVPD Kronos monitor nodes which are connected to sensors at the 33kV power cable terminations at both Bangor and Llanfair substations with a server at the Bangor substation.

A Kronos permanent monitor which carries out On-Line PD Insulation Condition Monitoring was installed at each of the substations, to give accurate readings from both ends. In addition to this, there is a Transient Earth Voltage Sensor to detect high frequency PD pulses in the balance of plant – including switchgear, cable sealing ends, machine cable boxes and transformers. For measurement of high frequency PD within the cables, High Frequency Current Transformer Sensors were installed on the cable sealing ends. These were specifically built for high current and high load cables to carry out On-Line Partial Discharge measurements. Finally, the system was equipped with a power quality current transformer which operated below 200kHz for power quality measurements and detects currents at the power frequency of 50 Hz.

Photo evidence was included in Section 4 of the SDRC3 report ("HCCM_Systems_v1.01"), together with data collected by the HCCM System. An extract for the Service Support Contract was also provided in Section 5 with the supplier HVPD Ltd.

1.5. SDRC 4 - Factory Acceptance Test of MVDC Converters

Criteria

For this SDRC, the testing procedure and key findings from the testing process were to be detailed in a report which could be shared with all relevant stakeholders. This would allow any issues in the testing process to be pinpointed and highlight areas of potential technical and supply chain risks.

Performance

In this criterion, the report '**Factory Acceptance Test of MVDC Converters'** was delivered before the deadline of 30 November 2018, which contained details of the FAT testing procedure and key findings. One of the key findings is that a combination of existing testing standards for MVDC drives and HVDC transmission could be used to successfully test individual MVDC items of plant including the power electronic converter modules. These existing standards are listed below and show that a selected range of power electronics, Voltage Sourced Converter (VSC) Valve, AC Power Drive and general power electronic standards can be applied to successfully test the MVDC converters at the factory.

Table 2: Standards used for the development of FAT

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

The MVDC converters passed all agreed tests, including:

- Visual Inspection
- Dimensional Conformance
- Verification of Current Transducers
- Verification of Voltage Measurement
- Earth Continuity Resistance Check
- Cooling System Pressure Test
- Cooling System Pressure Drop
- Verification of Flow Switch

- Power Interface Board and Gate Driver Communication Verification
- Gate Driver Card Check
- Load Test

Furthermore, it was found that there was a drawback in the original FAT approach. The noise levels of the transformers were measured during the FAT process by using a sound meter at a 1m distance from the transformer during full load. However, this did not consider the impact of high orders of harmonic current content due to the MVDC converter switching. To deal with this problem, a sound barrier was installed in front of the transformer bay so that the noise level was dampened below the occupational health guidance limit.

Overall, this criterion was achieved ahead of schedule. A time and cost-effective approach for FATs for MVDC converters was presented and highlighted additional risks with the FAT process were discussed.

1.6. SDRC 5 – Installation of the MVDC Circuit

Criteria

The MVDC circuit was to be installed and a report detailing the onsite installation process incorporating photos of the installation and a detailed description of the installation procedure was to be published.

Performance

This SDRC was initially due to be completed in April 2019. However, due to building cost estimates that were materially higher than the original price points, which was identified in a 2018 price review, a redesign of the converter station buildings was carried out to mitigate impact on project innovation funding and thus, customers. A change request was submitted to Ofgem to delay the deadline for this SDRC to 10 July 2020. The request was granted, giving a **15-month extension to SDRCs 5-8**.

Despite the disruption caused by the Covid-19 pandemic, the MVDC circuit was successfully installed, and the report '**Installation of The MVDC Circuit Report**' was published to all relevant stakeholders by the end of July 2020. The document can be found on the ANGLE-DC website as "Installation of the MVDC Circuit v1.0".

The individual components of the circuit and their installation procedure were detailed in this report, covering:

- MVDC Modules
- DC Reactors
- Power Interface Transformers
- DC Switchgear
- Pre-Charge Unit
- Grounding Resistor
- Control Cubicles
- LV Motor Control Board
- Primary Colling System

In addition to covering installation of all the individual components and how the full system was installed and configured, additional value was added in this report through the provision of Section 4 – Considerations for Future Installations. In this section the impact of potential flooding was included after record-breaking rainfall in the project vicinity, and ways to mitigate flooding were included to give future developers more insights into potential risks. Specifically, surface and river flooding risk assessments should be based on extreme weather. And a raised design for the converter housing and cable entry can be considered to mitigate the risk of flooding.

In this report, some valuable engineering recommendations for future installations were identified, such as the installation of high-resolution cameras to allow remote inspections of the converter halls, reducing downtime for maintenance inspections. Alternative designs for the Heating Ventilation and Air Conditioning system were outlined and considerations that could potentially bring cost reductions were also discussed. These recommendations add further value by enabling future projects to deliver more cost-effective solutions based on the learnings of the SPEN Angle-DC project.

To summarise, this criterion was completed successfully by the end of July 2020. And photos of the sites were provided for both Llanfair and Bangor as evidence of the installation.

1.7. SDRC 6 - Publication of Circuit Condition Data Report

Criteria

For this criterion, a report was to be published detailing the findings from the HCCM system showing the condition of the AC system and how it changed after conversion to a DC system.

Performance

As described in the SDRC5 section, the deadline of SDRC6 was extended from 23 January 2020 to 23 April 2021, and the report **'Angle-DC Circuit Condition Data Report'** was published before the extended deadline. The document can be found on the ANGLE-DC website as 'Angle-DC_Circuit_Condition_Data_Report_v1.0'.

An AC/DC converter was installed at each end of the circuit and the major objective of the HCCM System was to monitor the condition of AC assets under DC stress in real time. In the report, results from a period of AC energisation in 2018 (before the conversion to DC) were presented and compared with those from a period of DC energisation after the conversion. It was found that the peak PD levels from AC energisation were at low to moderate levels, while the peak PD levels from DC energisation were also at low to moderate levels but with lower values throughout the monitoring period.

No major incidents have occurred since the commissioning of the HCCM System.

This report provided exceptional value, by allowing future project developers to see the performance of a MV distribution system after conversion from AC operation to DC and sharing learning of what may allow other developers to identify any issues with their own projects if they installed a MVDC system with similar topology and rating.

SPEN understand that the longer the operation period of the MVDC system, the more representative the collected results will be. Therefore, we intend to keep collecting circuit condition data and share with stakeholders in the future.

1.8. SDRC 7 – Operational Performance of the MVDC Converter Stations

Criteria

The criterion for this SDR was to show that the MVDC converter stations were successfully operating, and to provide information in the form of a report whenever the system was non-operational due to forced or unforced outages. The report was to summarise the operational performance since the commissioning of the MVDC converter stations.

Performance

As described in the SDRC5 section, the deadline of SDRC7 was extended from 23 January 2020 to 23 April 2021, and the report **'Angle-DC Verification and Validation Report'** was published before the extended deadline. The document can be found on the ANGLE-DC website as 'Verification_Report_v1.1_PUBLIC'.

The verification and validation report proved that the MVDC converter stations operated with satisfactory performance. To start with, it showed results of the steady state tests which varied active power (limited by rating) and power factor (limited between ±0.85 and 1). All setpoints were achieved successfully.

Besides steady state tests, dynamic tests were also conducted, by applying step changes on active power or AC voltage. In all cases the new setpoints could be followed while maintaining stability. The DC cable power quality was also monitored and findings were discussed in the report, which showed that the actual MVDC link harmonic levels were well below the modelled MVDC link harmonic values.

In addition, the EMI performance was investigated, as there was a risk that interference might occur with national rail infrastructure due to cables along the rail deck of the Britannia Bridge. After site measurements, it was found that the levels of EMI were within acceptable limits.

The report provided evidence that the MVDC system operated as intended. However, as it was installed in July 2020, followed by further initial adjustments, by the deadline of April 2021, the system operation time had not been long enough to produce meaningful figures on outages and energy availability. SPEN have a Service Level Agreement, which requires about 2 weeks of planned outages (Scheduled Energy Unavailability) per year. Forced Outage Rate, Forced Energy Unavailability and Energy Availability can be inferred from the planned outages, but the details of the service agreement cannot be shared due to confidential reasons. SPEN will publish any unplanned outage and unavailability data outside of the 2 weeks annual maintenance on its innovation website, following 5 years of operation.

1.9. SDRC 8 - Successful Dissemination of Knowledge Generated

Criteria

The knowledge and learnings from the project were to be disseminated to the industry in general, particularly to involved stakeholders (mainly other DNOs), through project progression reports, bi-annual workshops, annual conference presentations, an online project portal and the publication of the Project Close Down Report.

Performance

The dissemination of learning is where this project has thoroughly exceeded the initial aims and expectations by carrying out significantly more knowledge dissemination than originally planned, cost-effectively and to the benefit of industry. All original milestone project progression reports were uploaded to the Angle-DC website in a timely manner – note that due to the extension and delay, additional reports from 2018 to 2020 were only published annually in alignment with progress over that time. SPEN was keen to share learning and knowledge from the Angle-DC project with both internal and external audiences. In total, 19 learning dissemination activities were held, among which 5 were workshops, 10 were conferences, 3 were webinars and one was colloquium. More details of the events are as shown in the table below.

Table 3: Learning Dissemination Events

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
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

Event Title	Event Type	Format	Date
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
CIGRE Paris Session 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

Another key outcome of this project was the production of the CIGRE Technical Brochure TB875 on MVDC links through the Joint Working Group C6/B4.37. The production of this TB significantly increases the ability of other DNOs to roll out this technology within their networks. The validation and verification of the MVDC system brings confidence that the technology is ready to be deployed and gives a technical route to success. In addition, if more and more MVDC projects were carried out in the UK, it would bring a positive impact on the development of local supply chain for MVDC equipment.

Overall, this SDRC was achieved successfully. Knowledge and findings were broadly shared, showing the value of this project in proving the implementation of MVDC circuit technology, and in particular the conversion of existing assets from AC to DC in a cost-effective manner.

2. Cost Effectiveness

2.1. Overview

Overall, the project spend was slightly above what was anticipated in the updated Project Direction. There was a slight overspend, which was mostly taken from the contingency category. This was an overspend of £221k which was absorbed by the business as an additional commitment to protect customer investment. The budgeted cost, actual cost and variance of the main items in the project are shown in the table below.

Table 4: Budget and Variance

Item	Budgeted Cost (£M)	Actual Cost (£M)	Variance
Labour	1.815	1.78	-1.93%
Equipment	6.074	6.083	0.15%
Contractors	5.366	5.388	0.41%
Travel and Expenses	0.345	0.349	1.16%
Contingency	1.2	1.421	18.42%
Other	0.04	0.041	2.50%
Total	14.84	15.062	1.50%

There were some cost differences, impacted by Covid-19, in the execution phase of the project, and the converter station building prices received were twice as costly as had been originally forecast. To maintain cost effectiveness, a full redesign of the converter station building was carried out leading to an extension in time requirements but ultimately the best value for money for consumers.

2.2. Cost Efficiencies

Cost efficiencies were realised throughout the project through effective project management and monitoring of any potential changes to costs. Benefitting from a strong initial design and robust plan, the overall project was cost effective, though there were unexpected increases due to the additional study required for the EMI along the railway bridge and the noise mitigation strategy required for the transformers. The decision to request additional time to allow for the converter station building redesign was strongly influenced by SPEN’s focus on ensuring a cost-effective solution for customers.

The project achieved a net comparative capital investment saving of £2.1 million, and potentially as much as £2.9 million, compared to the conventional reinforcement approach which would have been required to address the challenges facing the North Wales 33kV distribution network – a total interconnector capacity uplift of 5.7 MW.

Also, through enhanced voltage and reactive power control via the MVDC link, subsequent reductions in losses of around 20% can be achieved, which is equivalent to a £630k annual saving.

If the solution of the Angle-DC project were rolled out in a targeted way across the UK, there would be potential savings of up to £396 million by 2050.

2.3. Significant Variation in Project Costs

The primary variation in cost was due to the MVDC equipment which had a cost of £9.6 million, an increase of £813k, this variance was covered by the contingency budget. The reason that the cost was significantly higher than anticipated was due to the costs of the redesigned converter station building and a slight increase in the cost of the MVDC converter system itself. These additional costs were absorbed by SPEN to protect customer investment. The reason for this significant variance was due to the uncertainty in cost for equipment in a relatively novel technology area.

2.4. Contingency Budget Use

The contingency budget was used almost entirely to cover the additional converter station building and converter costs (as described in the previous section), with additional funding input from SPEN. This was the most beneficial way to proceed with the project when considering the cost to end consumers. Despite this additional spend, the project has still provided a cost-effective solution.

3. Project Management

3.1. Project Management Overview

Proactive project management was key to the successful delivery of this project. It was in a substantial part, achieved through actively assessing and managing potential risks as well as careful control of scope, costs and programme. Key risks that arose and were effectively managed include the interference with the railway bridge, noise issues with the transformer building and the cost mitigation approach for the converter station building. The project management approach led to a project that surpassed its initial aspirations.

The final stages of the project proceeded through the restrictions and manufacturing issues that occurred because of the Covid-19 pandemic. The successful delivery of the project, despite these challenges, highlights how well the project was being managed, with considerations for increased lead times on component delivery, travel restrictions and extended delivery timelines for on-site work due to a restriction on the number of people in certain areas. The project team managed to solve these challenges through close project management and delivered the project to a high quality while ensuring the health and safety of the people working on the Angle-DC project.

Risks and opportunities were well tracked, and the progress of the project was carefully monitored throughout – as can be seen in the progress reports which have been published. Proper project management process turned delays into an opportunity to provide better outcomes in other areas such as focussing on the publication of internationally recognised standards and papers, while the project was delayed. The issues faced during the project were also resolved and utilised as an opportunity to offer learning beyond what was initially described in the proposed solution.

3.2. Management of Change and Risk

The risks were managed through the maintenance of a risk register with a key risk management process, which highlighted decision points and risks associated with them. Through diligent monitoring of these risks, the project was able to foresee issues and establish mitigations and contingency approaches to deal with them. The management of these risks also enabled lessons to be learned which could be disseminated to de-risk future MVDC projects.

3.2.1. Risk Register

The risk register was maintained throughout the project period, with regular risk meetings held to identify and discuss additional issues. Task Forces were also set up to manage the key risks, e.g. the Covid-19 issues, converter station building redesign, and the transformer noise issues. An example of the risk register and risk identification approach is given below.

SECTION 10 RISK MANAGEMENT

To ensure successful delivery of expected benefits and learning objectives of the ANGLE-DC Project, we proactively identify risks to the project and provide mitigation plans. The risk register is being updated regularly, during the project. All identified risks are list under four major risks areas (technical, procurement, operational and project management) and are listed in Table 2.

Seven risks identified in the table have been updated with the current perception of the Project team. These are:

Risk 1.03 **Harmonic interference:** Lack of converter modelling information for AC/DC interactions studies, which will put the Common Safety Method Risk Evaluation and Assessment approval at risk. This risk has risen from 25/40 to 30/40.

Risk 2.03 **Cost of Installation:** Following the energisation of the circuit and final contract settlement, this risk is now closed.

Risk 2.04 **Easements/ wayleaves:** Following the negotiation and bank transfer with the various land agents, this risk is now closed.

Risk 2.06 **Damaged equipment:** Following the delivery of all items to site, the risk has not materialised, and this risk is now closed.

Risk 2.08 **Delay in delivery of Converters** Following the delivery of all items to site, the risk has not materialised, and this risk is now closed.

Risk 2.11 **Delay in delivery of network control system:** A continuing risk is the delivery of the network level control system. This item is critical to the operation of the MVDC link and the converter commissioning cannot be completed without it. SP Energy Networks has awarded a contract and begun development. This risk is reduced slightly from 25/40 to 20/40.

Risk 4.01 **Higher costs:** There two commercial contracts that are yet to be closed, but these are expected to remain within budget contingency. The MVDC supplier has submitted additional costs claims related to working during the COVID 19 crisis. Overall, the score for this risk has slightly increased from 25/40 to 28/40.

Risk No.	Issue	Risk Description	Potential Impact	Control & Contingency Measures	Overall Risk (2-40)
1. Technical risks					
1.01	Existing cables integrity with DC	Cables are unsuitable for DC operation at 27kV either due to age or type.	Project halted; delayed reinforcement and no demonstration of conversion to MVDC.	1. System operating DC voltage level kept at or below peak AC voltage level (27kV). 2. Conductor temperature limited to a maximum of 50°C for all cables. 3. Short time 27kV DC testing completed on the circuit with no problems.	5
1.02	Existing cable joints integrity with DC	Joints are unsuitable for DC operation at 27kV due to age or type.	Project halted; delayed reinforcement and no demonstration of conversion to MVDC.	1. System operating DC voltage level kept at or below peak AC voltage level (27kV). 2. Conductor temperature limited to a maximum of 50°C for all cable's types. 3. Short time 27kV DC testing completed on the circuit with no problems.	10
1.03	Harmonic interference	Superimposed high frequency interference on MVDC in existing cables couples with third party services.	Delay and additional cost to project in order to resolve problems for third parties.	1. Perform a study of VSC converter harmonics and determine likely interference on telecom and transport signalling after a study of installed services and harmonics to be generated. VSC converter filters/switching frequency to be designed to be adequate by converter supplier. 2. CSM RA process to be carried out with Network Rail. 3. Cable testing on harmonic impedance completed.	30

Figure 1: Risk register example.

3.2.2. Project Programme

The project programme was maintained closely and was aligned with the SDRC. Control of this programme allowed several opportunities to be taken, such as the installation of the HCCM system during a rare scheduled limited outage on the Llanfair – Bangor Grid 33kV cable and the early appointment of HVPD as the supplier of the monitoring equipment to mitigate the risk of delay in procuring the monitoring system.

SDRC	Status	Due Date	Comments
SDRC 1 - Publication of HCCM Technical Specification.	Complete	17/06/2016	Shared with all relevant stakeholders.
SDRC 2 - Publication of Converter Technical Specification.	On Track	24/02/2017	Procurement brought forward, with Technical Specification informed by design of selected supplier.
SDRC - 3 - Commissioning of HCCM system	On Track	15/09/2017	Not started, but expected to be completed ahead of schedule.
SDRC 4 – Factory Acceptance Test of MVDC Converters.	On Track	28/09/2018	Not started, but expected to be completed ahead of schedule.
SDRC - 5 Installation of MVDC Circuit/ Commissioning of Converters.	On Track	12/04/2019	Not started, but expected to be completed ahead of schedule.
SDRC 6 - Publication of Holistic Condition Monitoring data.	On Track	23/01/2020	Not started, but expected to be completed ahead of schedule.
SDRC 7 - Publication of operation performance of MVDC converters.	On Track	23/01/2020	Not started, but expected to be completed ahead of schedule.
SDRC 8 - Effective Knowledge Dissemination.	On Track	16/04/2020	Website updated. Two papers submitted to IET ACDC conference.

Figure 2: High Level Schedule

The programme was changed significantly following the cost clarification for the original converter station building – this was agreed with Ofgem, and the updated target dates agreed are shown below:

No	Item	Original Date	Proposed New Date
1	SDRC 5 Installation of the MVDC circuit	12/04/2019	10/07/2020
2	SDRC 6 Publication of circuit condition data report	23/01/2020	23/04/2021
3	SDRC 7 Publication of operational performance of MVDC converter stations	23/01/2020	23/04/2021
4	SDRC 8 Successful dissemination of knowledge generated	16/04/2020	16/07/2021
5	Project Completion	16/04/2020	16/07/2021

Figure 3: Modification to the programme accepted by OFGEM

The modification of the programme allowed a more cost-effective solution to be provided for the customers and led to greater values overall for the project.

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Appendix

Documentation Provided

A1. Project Progress Reports

1. Angle DC Progress Report June 2016
2. Angle DC Progress Report December 2016
3. Angle DC Progress Report June 2017
4. Angle DC Progress Report December 2017
5. Angle DC Progress Report June 2018
6. Angle DC Progress Report June 2019
7. Angle DC Progress Report June 2020
8. Angle DC Benefits Report - October 2022
9. Angle DC Close Down Report

A2. Technical Documentation

10. Operation and Control of MVDC Demonstration Project in the UK
11. Verification Report
12. Installation of the MVDC Circuit
13. Angle DC Circuit Condition Data Report
14. Medium Voltage DC Technical Brochure CIGRE
15. MVDC Link System Technical Specification
16. HCCM System Technical Specification
17. HCCM Systems
18. Factory Acceptance Test of MVDC Converters

    Factory Acceptance Test of MVDC Conver