Operation and Control of MVDC Demonstration Project in the UK: ANGLE-DC

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Abstract: The emerging Medium Voltage Direct Current (MVDC) distribution networks are becoming more attractive due to their flexible power flow control and lower losses compared to traditional AC networks. This will significantly increase the wide uptake of renewable energy sources. The optimum utilization of the existing assets is an important aspect of grid upgrading and planning. One feasible option is to convert existing MVAC lines into MVDC operation. One of the practical demonstrations is the "ANGLE-DC" project which is also the first MVDC link in the UK. This paper highlights the innovative approach, challenges and key benefits delivered by the ANGLE-DC project.

Key words: Medium voltage DC, MVDC converters, operational challenges,

1.0 Introduction - Background and Motivation

Intending to encourage and stimulate innovation amongst power system network operators, various UK governmental initiatives such as the Low Carbon Network Fund (LCNF), Network Innovation Allowance (NIA) and Network Innovation Competition (NIC) have been in place since 2010 [1]. These innovative approaches enable cost savings to both domestic and industrial consumers within the UK. The project, entitled ANGLE-DC, is funded under the NIC scheme with a total project budget of £14.8 million [2]. It is considered to be Europe's (if not the UK's) first example of an embedded dc link to be used within a distribution network Error! Reference source not found.. The project started in the first quarter of 2016 and is expected to commission by 2020.

SP Energy Networks (SPEN) has proposed the interconnection between two areas of their north Wales licence area, where there is an existing connection to the island of Anglesey [1]. Anglesey is located off the north coast of Wales, separated from the mainland by the Menai Strait, as shown in Figure 1. The Anglesey area is rich with renewable energy resources and often produces more energy than is uses. As of Error! Reference source not found., by 2016 the connected and contracted renewable generation connections have reached around 150 MW. Therefore, the distribution network operator regularly needs to export surpluses to mainland Wales. With forecasted load and generation growth, the 33 kV network connection (between Llanfair PG and Bangor substations) is identified to be operated near its designed thermal limits.

Figure 1 ANGLE-DC Project Location

In general, the traditional solution to remove such network bottlenecks is to reinforce the system by building new electricity infrastructure. However, this is an expensive option; often requiring lengthy planning consent processes and introducing new electricity infrastructure. On the contrary, the ANGLE-DC project enables to maximise the capacity of the existing network and avoid the need for extra reinforcements. Further, converting AC assets to DC operation will enhance the thermal capability of the circuit in a timely manner. It has been calculated that a total savings of £18.67m could be gained from the ANGLE-DC trial, in addition to the CO_2 emission reduction. The savings would be in the form of a) Net capital investment saving associated with the incremental capacity of 30.5MW, b) £7.57m for wide area loss reduction by the end of 2030 and £15.77m by the end of 2050. This pilot project will incorporate a novel technology as part of the set of solutions for network reinforcement and renewable connections.

2.0 Project Overview and Delivery

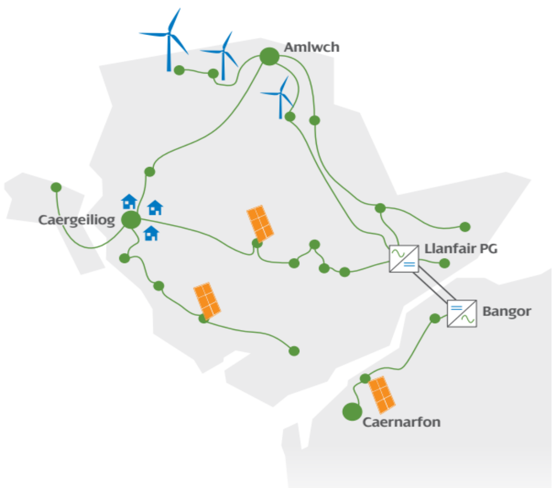


Figure 2 ANGLE-DC Substation Locations Error!

The network strengthening will take the form of an MVDC link operating at ±27 kV through existing repurposed 33 kV cable and a small section of overhead line (allowing transient faults to be examined). The scheme rating is 30 MVA. As the electricity demands in the region increase, uncontrolled power flows are putting the system at risk by exceeding thermal limits of the cables and overhead lines.

The MVDC link will enable improved power flow and voltage control. Converting AC assets to DC operation will also enhance the thermal capability of the circuit **Error! Reference source not found.**. This will showcase the effectiveness to unlock capacity from the existing circuits which can be used to facilitate the integration of renewable resources. The AC amplitude of 33 kV will be converted to ±27 kV DC giving a maximum theoretical increase in cable capacity of 43%. However, because the cables are old and not designed for DC operation, the maximum cable temperature will be kept, from the normal 65°C, to 50°C by reducing the maximum DC current from 219A to 188A. Further, this project demonstrates that AC assets can be used for DC operation by real-time condition monitoring of assets in pre- and post- DC conversion.

One of the main objectives of the project is to build confidence in deploying MVDC technologies by other UK Distribution Network Operators (DNOs) and triggering the MVDC supply chain. This will move MVDC from technology readiness level (TRL) 5-6 to 7-8. The other benefits for customers can be identified as follows **Error! Reference source not found.**,

1. Increasing the capacity for load and generation connections while reduced Nuclear Power transfer via the parallel 33 kV network.
2. More precise control of the flow of power in the distribution circuit for improved efficiency to avoid naturally occurring AC overloads.
3. Control of voltage at either end of the distribution circuit to enhance the flow of electricity to customers.
4. Control of reactive power flow at both ends of the distribution circuit.
5. Due to the improved voltage control, lower losses and save energy in the wider distribution network.
6. Fault level decoupling between distribution systems.

The project runs from early 2016 to 2020 and is divided into six main work packages (WP). Each WP contains a distinct workstream, essential for the completion of the project **Error! Reference source not found.**. Table 1 below shows the main tasks expect to deliver by each WP. By April 2020, factory acceptance testing (FATs) of MVDC converters and MVDC-link site acceptance testing (SATs) have been completed. Further, the Holistic Cable Condition Monitoring (HCCM) system has been commissioned which is an important task of the project.

Table I
ABGLE-DC Project Delivery

WP	Main Task
1	**Detailed design:** Development of MVDC converter and HCCM system technical specifications and MVDC link control strategy.
2	**MVDC link:** MVDC converter equipment production, testing, installation, and commissioning.
3	**New AC circuit:** Procurement, production, testing, installation, and commissioning of the backup AC parallel circuit.
4	**HCCM system:** HCCM equipment production, testing, installation, and commissioning.
5	**Data analysis:** Data collected from the HCCM system and MVDC link will be collected, analysed, and shared openly.
6	**Knowledge and learning dissemination:** Partnership with Cardiff University to publish and share learning.

3.0 The MVDC Link: Construction of New Assets

The main distribution network on the Isle of Anglesey is made up of 33 kV substations, cables, and overhead lines. The low-carbon generation on the island is located to the north, south and south-west of the island, however, the area with the greatest demand for power is at Caergeilliog, some distance away from the generation. The Anglesey 33 kV network is currently connected to the mainland between Bangor and Llanfair PG with a double AC circuit. This consists of 0.5 km overhead line and 2.5 km of cable, with a section of the cable running along the Britannia Bridge.

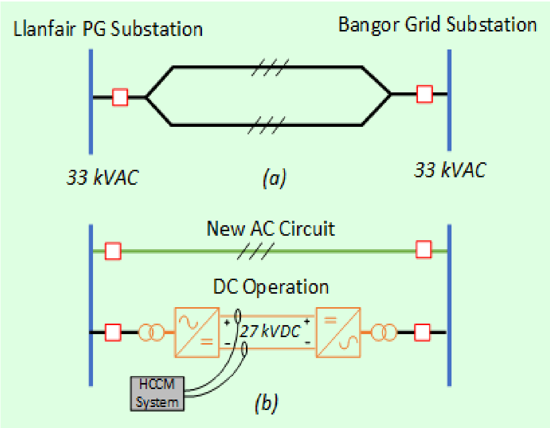


Figure 3 MVDC Link (a) Existing Connection (b) Proposed connection

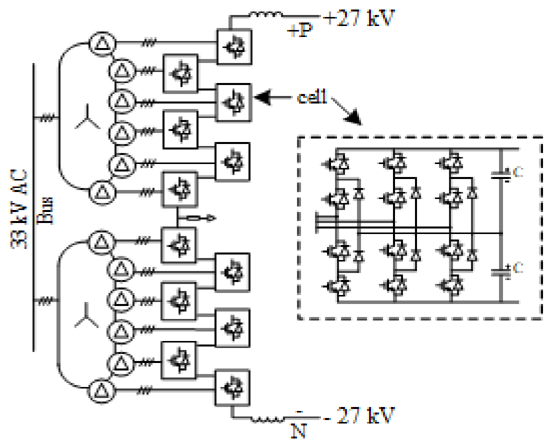


Figure 4 Cascaded NPC Structure

One of the cables is a 40-year old paper insulated cable. The project will build a converter station at either end of this circuit, which will then switch the current from AC to DC, and back again as shown in Figure 2. Figure 3 shows the existing network configuration with double 33 kVAC circuit arrangement and the proposed New 33 kVAC circuit & existing 'double' circuit converted to DC operation.

3.1 Holistic Cable Condition Monitoring System

As shown in Figure 3(b), a HCCM will be installed on the original circuit to record information on how the circuit is ageing under DC operation **Error! Reference source not found.**. The project will demonstrate on-line Partial Discharge (PD) monitoring systems. These are to be used to give an indication of PD based degradation and trend in time with other operating stresses which can influence PD including voltage ramp up/down, overvoltages and ripple from power converters. Further, this HCCM facility will provide evidence of incipient faults in the cable allowing planned maintenance to be undertaken in advance of a fault occurrence, thus minimising down-time while cable repairs are undertaken.

The HCCM will record this information for a minimum period of 12 months. This task is important because the observed results will be critical in determining whether future AC to DC conversion on existing circuits is feasible.

3.2. The ANGLE-DC Converter

The main imperative for the chosen technological solution is that it meets the functional requirements of the scheme. Due to the technological maturity of the 3L-NPC, a special designed cascaded 3L-NPC (C3L-NPC) has been deployed in the ANGLE-DC project.

The C3L-NPC achieves a lower capital investment than MMC without sacrificing the scalability and modularity of the design. The converter comprises of 12 cells (pole-to-pole), each of which is a 3L-NPC using a 4.5 kV IGBT module as shown in Figure 04. A high impedance dc grounding is applied at the mid-point of the converter to protect the C3L-NPC from earth faults **Error! Reference source not found.**. Therefore, this is a rigid bipolar system without monopolar operation mode.

The proposed circuit configuration consists of four identical voltage source converters (VSCs) with C3L-NPC topology using PWM strategy. Each pole consists of 6 cells connected to the 33 kV bus through inverter transformer in delta/star configuration. The total voltage at the inverter PCC is the sum of all the cell voltages from both poles.

4.0 Academic Engagement

4.1 Steady-State Analysis with ANGLE-DC Link

In **Error! Reference source not found.**, a real-time control method for an MVDC link was proposed, in which the active power flowing through the grid transformers (GTs) is used to determine the set-points of an MVDC link. GTs are the transformers that supply power to the network. This method is called GT-based control. The GT-based control requires only measurements at the GTs rather than the load and generation data at each load point (i.e. substations) of the network.

This work considered control strategies with multiple objectives, i.e. power loss reduction (PLR), feeder load balancing (FLB), voltage profile improvement (VPI), and compromise strategies providing trade-offs among them. The response curves of these control strategies were developed through offline studies, where a multi-objective Particle Swarm Optimization (MOPSO) method was used. Assessments and comparisons between different control strategies were carried out.

Taking half-hourly time steps, power losses of the Anglesey network with the MVDC link using different control strategies are shown in Figure 5. The power losses of the network when the link is operated in AC are used as a reference case. It can be seen that, with the MVDC link, regardless of the control strategy used, power losses of the

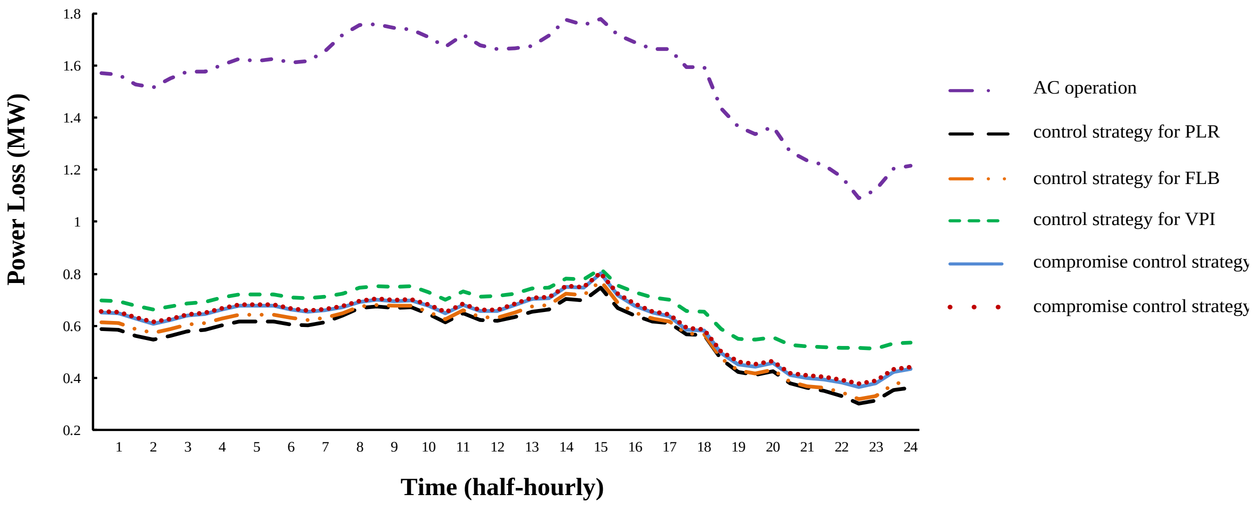


Figure 5 Power losses over a day of the network by using MVDC link and the original AC operation

network were reduced significantly compared to those when the link is operated in AC. Comparisons between control strategies showed that the one for voltage profile improvement led to higher power losses than other strategies. This is due to the extra power injections from the MVDC link for voltage regulation. Power losses obtained with the strategy for power loss reduction remained the lowest over the day, and losses obtained with the strategy for feeder load balancing were the second-lowest. The two compromise control strategies achieved medium performances among these objectives.

From Figure 6, it can be seen that the MVDC link can increase the DG hosting capacity over the AC operation. The control strategy for feeder load balancing achieved the highest DG hosting capacity, followed by the control strategy for power loss reduction, and the two compromise control strategies. With the MVDC link, an increase of DG hosting capacity up to 15% can be achieved in the Anglesey network.

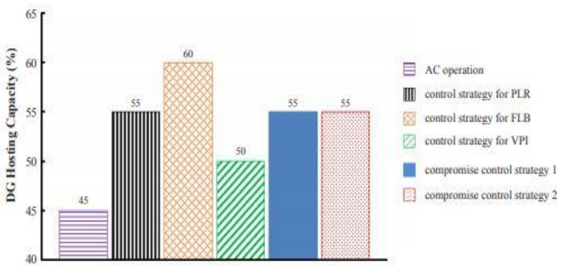


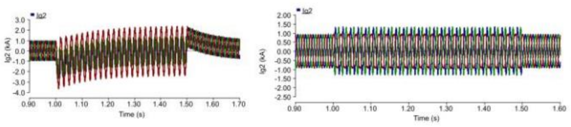
Figure 6 DG hosting capacity of the network by using MVDC link and the original AC operation

4.2 Dynamic and Reliability Analysis of MVDC Converters on the ANGLE-DC Link

a) Converter Operation Modes and Dynamic Control

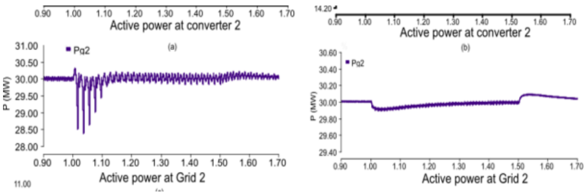
The primary objective of the MVDC link is to use the converters at both ends of a distribution network to control the power through the link and the AC voltage at each. In line with this objective, the Bangor Grid substation is supposed to operate as DC voltage and reactive power/AC voltage controller (Vdc-Q) while the converters connected to Llanfair PG substation is active power and reactive power/AC voltage control mode (P-Q) **Error! Reference source not found.**. As the proposed MVDC link is made up of C3L-NPC converters, to maintain the DC voltage difference of the two capacitors of each upper and lower arm of the NPC cell, a DC voltage balancing controller is required.

The operation of C3L-NPC MVDC converters under unbalanced condition results in undesirable oscillations in the active, reactive powers and DC voltage. A fault ride through scheme called *dual inner current loop controller* has been used to mitigate the impact of negative sequence harmonics. In distribution line faults, roughly 75% - 80% are asymmetric line-to-ground faults, very often caused by physical contact **Error! Reference source not found.**. Transient behaviour of the proposed MVDC link, to a single line to ground faults (SLG) fault at the PCC, is tested based on simulation studies in the PSCAD/EMTDC. The transient behaviour of the C3L-NPC converters with and without the controller is shown in Figure 7. It can be observed that, with the controller, the oscillations are mitigated substantially and thus the converters can be operated under grid disturbances.



(a) (b)

Figure 8 Current response under line to ground fault; (a) without controller (b) with controller



(a) (b)

Figure 7 Simulation results for line to ground fault at PCC; (a) without controller (b) with controller

As shown in Figure 8, the proposed controller works well in maintaining the AC voltage response. The currents became more sinusoidal when the proposed controller is implemented. Therefore, the harmonics at the AC side of the converter can also be mitigated.

(b) Reliability of the ANGLE-DC Converter

In general, VSCs are comprised of a large number of power electronics devices which are prone to fail at any time. The stochastic failure nature of components and the converter configuration are required to consider when selecting a suitable VSC. In **Error! Reference source not found.**, several candidate VSC topologies have been compared with the redundancy required to achieve >99% availability with different preventive maintenance intervals. Due to the configuration C3L-NPC shows the highest failure rate per pole, thus it requires more redundant cells to maintain the same availability as other VSCs.

After selecting the optimum redundant modules, the reliability of each VSC is shown concerning operating years in Figure 9. It can be noted that the C3L-NPC has better reliability over the state-of-the-art two-level (2L) VSC and 3L-NPC at the ANGLE-DC voltage level.

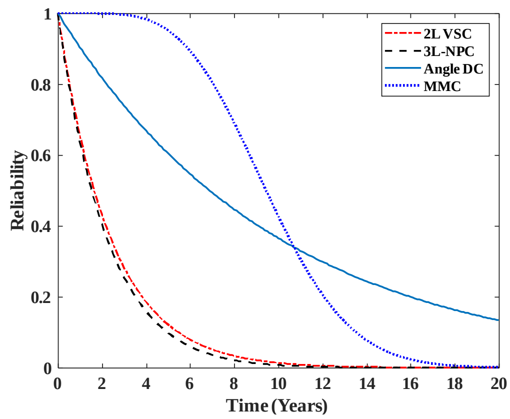


Figure 9 Reliability of 2L-VSC, 3L-NPC, C3L-NPC and MMC at ±27 kV MVDC level

Although the reliability is comparatively lower than the MMC, the lower capital investment of ANGLE-DC converter is one of the decisions making factors for the selection.

5.0 Conclusion

The ANGLE-DC project aims to convert an existing AC circuit into DC operation, in order to enable improved power flow and voltage control while enhancing the thermal capability of the circuit in a timely manner. Various techno-economic-social analyses suggest that the ANGLE-DC project shall deliver the anticipated goals. Use of existing assets for future network expansion shall minimise the capital investment significantly. Therefore, the practical experience gained from this project will be valuable for removing system bottlenecks with rapid load growth together with ambitious low-carbon and net-zero emission goals.

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