NETWORK INNOVATION COMPETITION – ANGLE DC PROJECT

INSTALLATION OF THE MVDC CIRCUIT REPORT

JULY 2020

ANGLE-DC

Version:	1.0	
Authored by:	Andrew Moon	– Senior Engineer and Project Manager
	Greg Shirley	– Innovation Engineer
Approved by:	Kevin Smith	– Lead Engineer and Principal Project Manager
	James Yu	– Future Networks Manager

EXECUTIVE SUMMARY

This report describes the components of the Medium Voltage Converter Stations and associate installation process, which was completed in July 2020. The report details the building equipment layout and describes each piece of main plant. The installation process for each piece of main plant is provided, together with photos at either Llanfair PG and Bangor Grid sites as evidence of the installation. Key learning and recommendations for future projects is detailed in the final section of this report. This report will serve as the evidence of ‘Installation of MVDC circuit’ to fulfil the requirement set out under Project Direction.

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SECTION 1 INTRODUCTION

ANGLE-DC aims to demonstrate a novel network reinforcement technique by converting an existing 33kV AC circuit to DC operation at ±27kV. The existing distribution network is increasingly strained due to growing demand and a high penetration of distributed generation. The conventional AC network has limited controllability and flexibility, two fundamental attributes required as the network evolves and becomes increasingly complex. ANGLE-DC will utilise an existing 33kV AC circuit ,comprising cable and overhead line sections, to establish a DC link. The condition of AC assets, under DC stress, will be monitored in real time using a Holistic Circuit Condition Monitoring System (HCCM). The AC/DC converter station buildings have been constructed and the MVDC converter equipment is now installed at each end of the circuit.

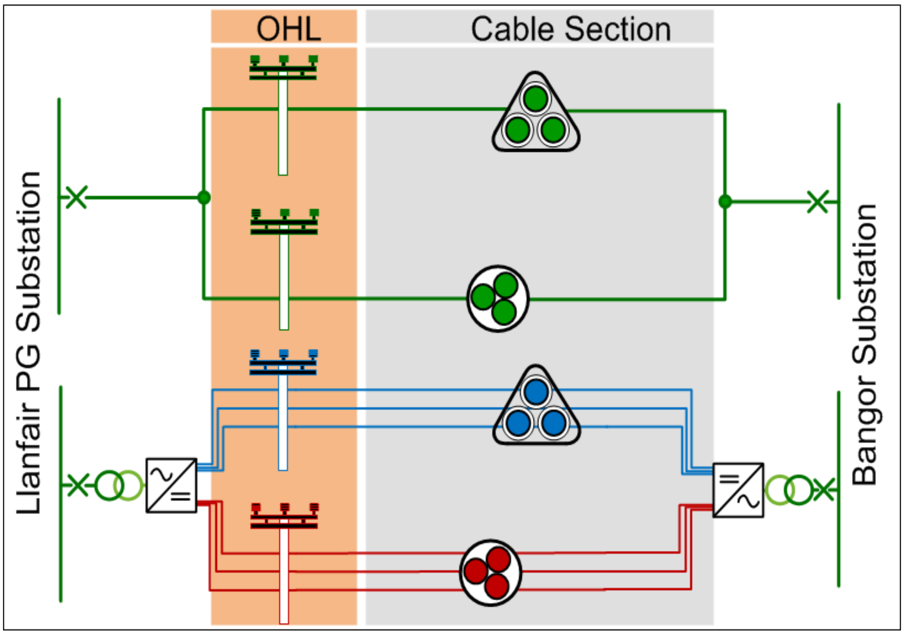


Figure 1. High level drawing of conversion from AC to DC for the Angle DC project. The origianl AC double circuit (top) and the new stations and transfromers intalled either side of the converted MVDC circuit (bottom). The positive 27 kV pole is in blue and the negative pole in red.

This report details the onsite installation procedures and incorporates photos of the installed equipment. Section 1 introduces the MVDC system and describes each of the component's parameters. Section 1 provides a description of each component's function and includes the installation procedures and installation photos for each. Finally, 3.9.1 considers the learning from Angle-DC from an installation perspective and options for future MVDC projects.

SECTION 2 MVDC SYSTEM

Physically, each station is separated into 5 main areas as shown in Figure 3. These areas are the: 1) control room 2) valve hall, 3) system cooling bay, 4) MVDC switch room and 5) semi enclosed transformer bay. The control room houses the LV power distribution and converter motor control panels, secondary cooling system, the converter control panel, UPS and the network level control system. The valve hall contains the DC converter modules, DC reactors and primary cooling system pipework. The system cooling bay contains the fans, heat exchanger and coolant pump skid. The MVDC switch room houses the DC switchgear and HCCM system. Finally, the transformer bay house two interface transformers, which connect each converter station to the AC network.

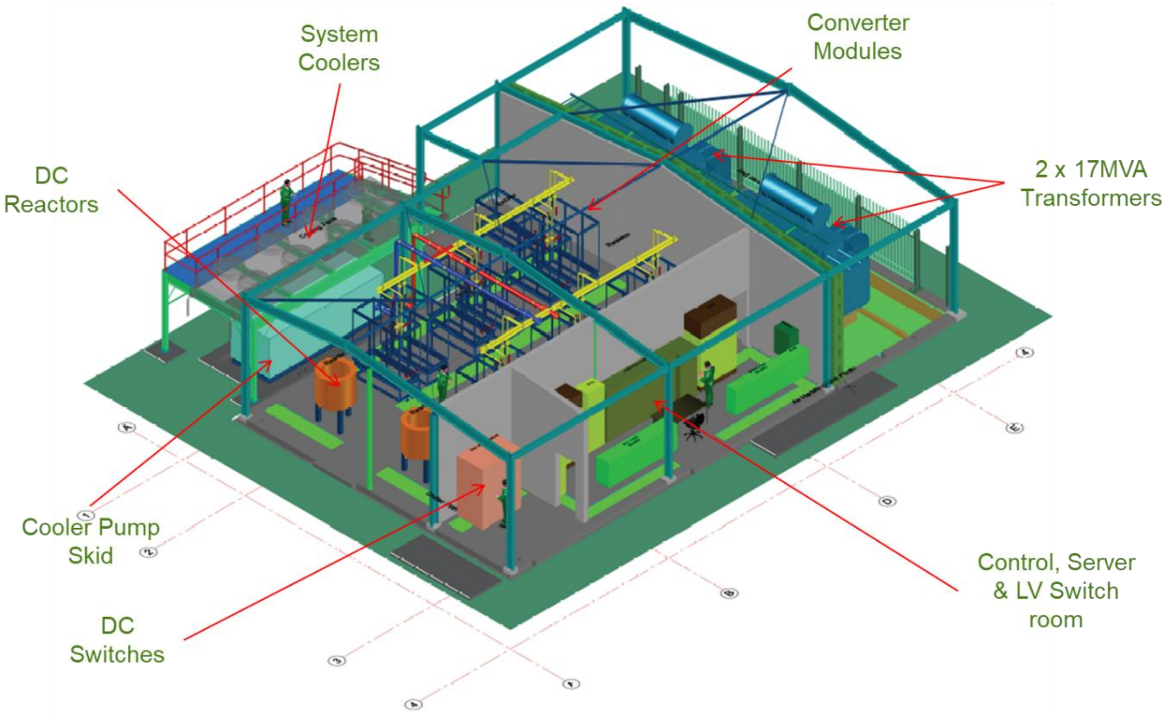


Figure 2. Detailed 3D General Arangement of the MVDC stations.

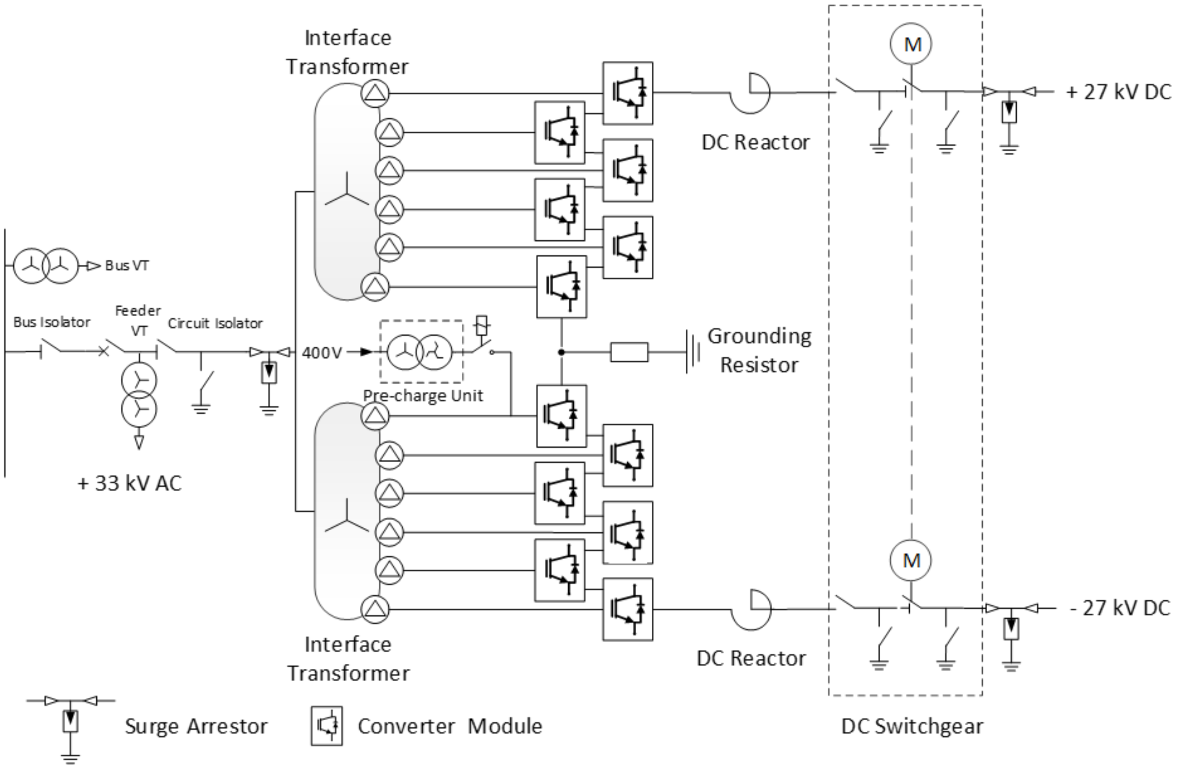


Figure 3. A single line diagram of one inverter station showing the Angle-DC single line circuit configuration and high level MVDC link topology. Arrangements shown are symmetrical for both ends

The two interface transformers are rated at 17 MVA and are of a unique design, with 1 HV and 6 LV windings; 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. Therefore, there are 36 MV cables running from the transformer bay to the valve hall converter modules.

The 12 converter modules in each station, 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 before the 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 200V. The station's 2-pole isolators can only be reclosed by Authorised Personnel following rectification of a DC fault.

SECTION 3 INSTALLATION PROCEDURES

3.1. MVDC Modules

As discussed in Section 2, the NPC modules convert 2.1 kV RMS AC to 4.1 kV DC. Figure 4 shows a single line representation of one phase of an NPC converter. Point 1 is the AC connection, which requires 3 AC cable terminations per module. On the DC side, point 2 shows the DC terminal, which requires a DC bus connection per module, so each group of 6 modules can be interconnected in series. Point 3 on the diagram is the heat exchanger, for the Insulated Gate Bipolar Transistor (IGBT) cooling. This requires flow and return coolant pipes to transport the heat away from the modules to the external heat exchanger. Point four on the diagram represents the gate switching signal terminal. Physically, this is made up of control system single mode fibre and LV power connections to the control module. The DC bus capacitor banks and voltage and current sensors (shown) come preinstalled with the modules.

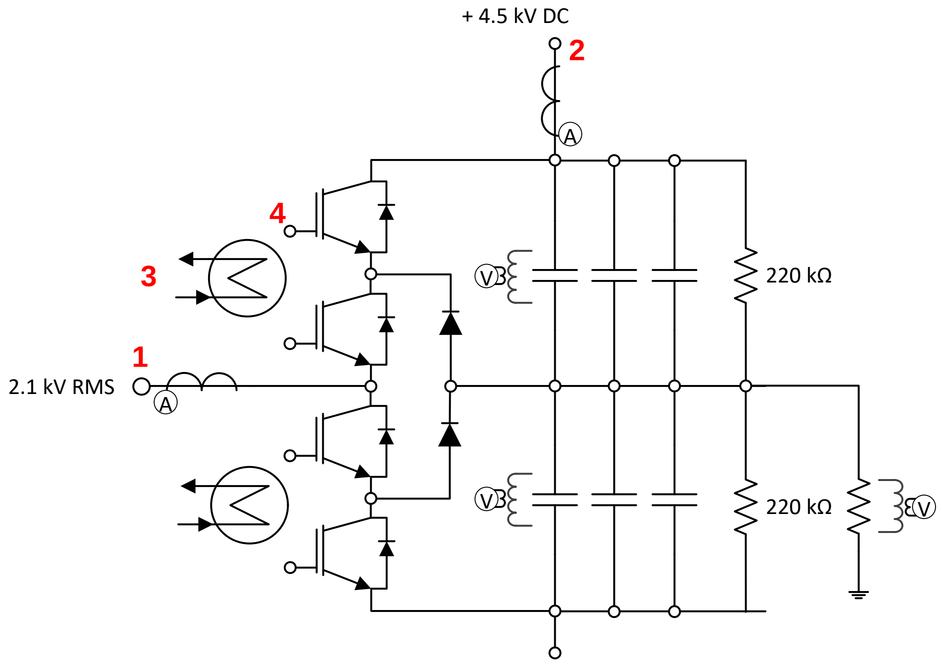


Figure 4. Single phase topology of an NPC Converter module with cooling circuit for IGBT cooling.

Figure 5. Photograph of a converter module before it's installed onto its base and post insulators.

At 2200 kg each of the 12-inverter modules were dropped at the rear double doors of building using a telehandler. The modules were then moved into their final position within the valve hall using skids. H-frames were used to lift the modules from the skids onto the post insulators, which were secured to the base. This concluded the mechanical installation for the modules.

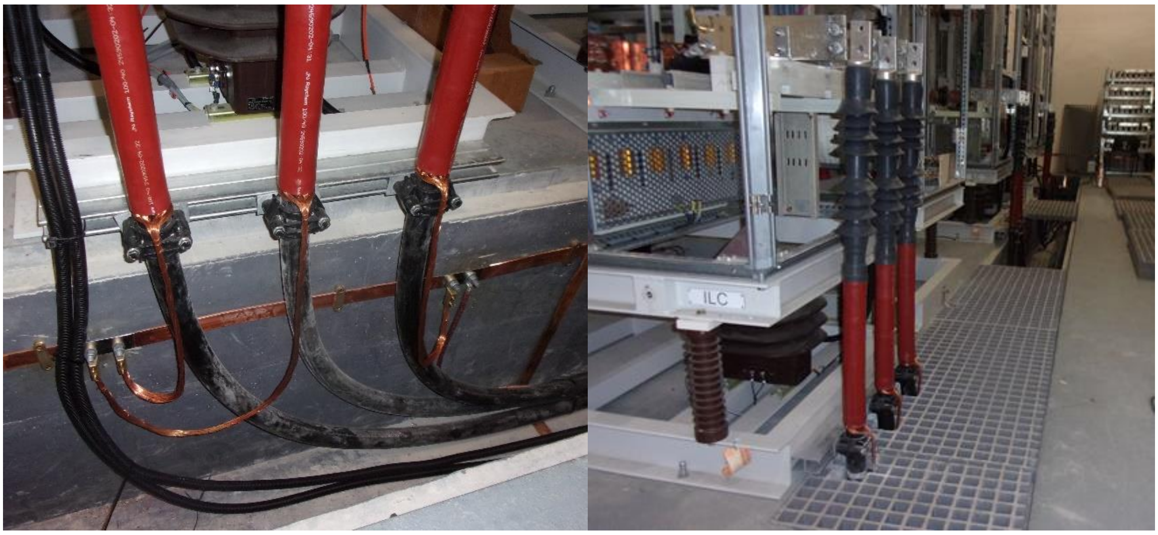


Figure 6. MV AC terminations onto converter module AC flags.

Once mechanically installed, the LV cable from the UPS and control cables were run between each module and terminated. The 36 AC cables were pulled and secured to the module cable cleats and terminated onto the AC terminal flags using cable lugs and bolts. The connections between the pre charge unit, to the AC side of one module in each station, was then completed as shown in Figure 6. Finally, the interconnecting DC bus bars were then installed between the modules, either side of the grounding resistor and DC reactors on the positive and negative poles.

3.2. DC Reactors

Since the DC reactors are an entirely passive electrical component, with no monitoring or control, these units were the simplest to install. At 525 kg each, a telehandler and H-frame were used to take the reactor from the delivery location to the final position within the valve hall. Once in position, these units were bolted to the floor.

The DC busbars from the last module, on each pole, was connected to each reactor and the DC cable terminated to the reactor flag using a cable lug and bolts. On the SDRC date of July 10th, 2020, the DC cable from the reactor to the DC switchgear was not yet installed but programmed for completion by mid-July.

Figure 7. Mechanically installed DC reactor with DC solid bus connection completed.

3.3. Power Interface Transformers

The transformers were transported from temporary long-term storage partially filled with oil. Each transformer weighs approximately 40,000+ kg. The units were transported with cooling fins and the conservators removed. Before each transformer was transported to site, a heavy lift crane was driven to its lifting position as per the lift plan. Once the transformers were at each site, the transformer low loader lorry was driven to the proximity of the crane and each transformer was lifted, swung and lowered to the skid way, situated just in front of the transformer bays. Each transformer was skidded on to jacks situated on each transformer plinth. Anti-vibration matts were placed beneath each transformer before they were jacked into their final positions. Each transformer was then bolted and mechanically secured.

Figure 8. Photograph of transfromers being slid into position at Llanfair PG substation. The farthest transformer can be seen with its fins and conservator fitted.

Once secured, the transformer conservators and radiators were lifted to position and fitted to each transformer. At this point, the oil in each tank was tested for moisture and impurities before each unit was topped up with oil to the nominal capacity of 11,000 L. At this point the transformers were mechanically installed.

Each transformer is protected from a fault condition within the transformer or on the DC side by the feeder protection panel. The SP Energy Networks protection panels have been extended to provide additional interface transformer protection relays, which include: Bucholz gas, winding over-temperature, inverse and definite time over-current, inverse and definite time ground fault. Each transformer comes with a marshalling kiosk which houses its protection interface and LV auxiliary wiring. Multicore cabling and LV cabling were run between the AC switchgear panel, MVDC control panel and LV motor control panel and terminated with the transformer marshalling kiosk.

Figure 9. MV AC cable running from the valave hall trenches (left) to the transformer bay (right). Cables have been cleated in a trefoil arrangement.

On the station MV side, the 18 x 500mm^2 Cu XLPE AC cables were run from the converter modules and mechanically fixed to the transformer bay partition wall with trefoil cleats. At the SDRC date of the 10th of July, the transformer MV connections were not yet complete. In mid-July, each cable was brought up from below and were fitted with Euromold tee connectors and then connected to the transformer bushings. The network AC cable was terminated within the transformer cable box during the cold commissioning phase, to simplify the commissioning requirements from an operational standpoint.

Figure 10. Semi-enclosed transformer bay showing mechanical completion of the two 17MVA transformers.

3.4. DC Switchgear

The DC switch gear was skidded into place through the access door within the MVDC switch room. These were bolted to the floor and earthed once in their final position. The LV supplies, which feed the motorised switch, and protection multicores were run from the control room station control panel and LV supplies and terminated within the DC switchgear interface unit.

As of the SDRC date of the 10th of July, the DC terminations within the break panel and riser panels were not completed. The multicore connection from the interlocking scheme and mimic control panel was also outstanding. The work is due for completion by the end of July 2020.

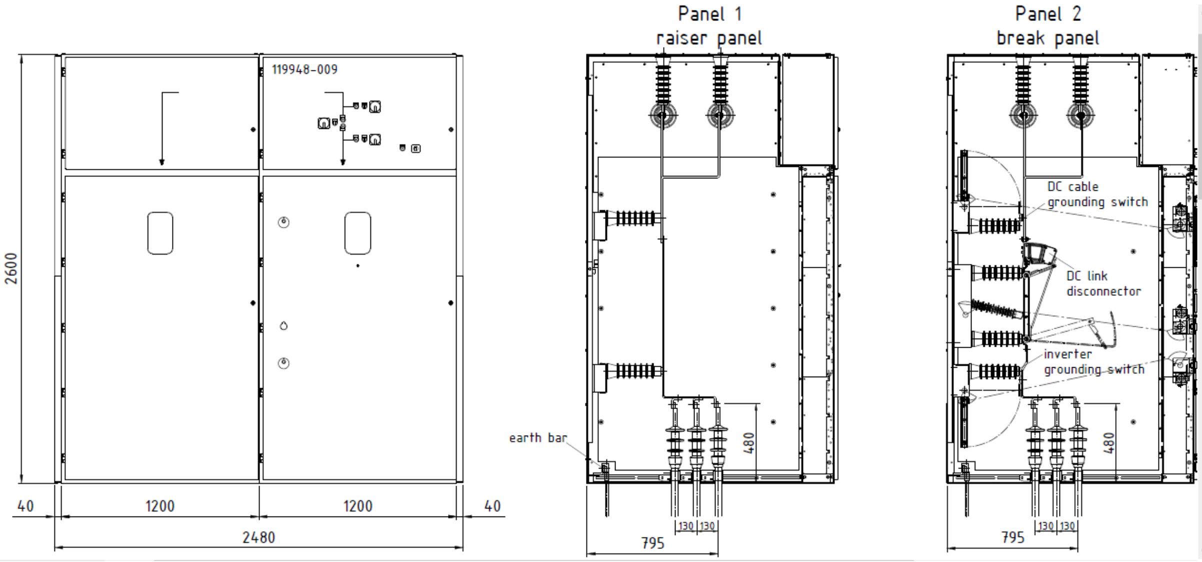


Figure 11. General arrangement of the DC switchgear.

3.5. Precharge Unit

The pre-charge unit is used to pre-charge the DC link in order to bring the voltage of the inverter system upto the same level as the AC network. This ensures that no damage to the inverters will occur due to inrush currents when closing onto the AC network. This is used instead of a pre-insertion resistor which is not present in this system.

The pre-charge unit consists of two components, a exciter transformer and a disconnector. Although mounted independently within the valve hall, both components are closely coupled and referenced collectively as the pre-charge unit as shown in Figure 12.

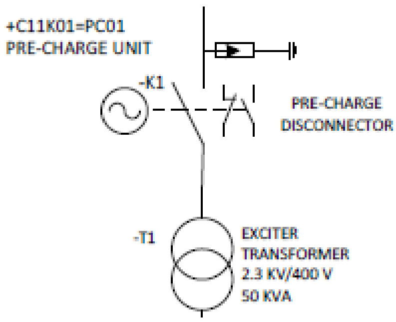
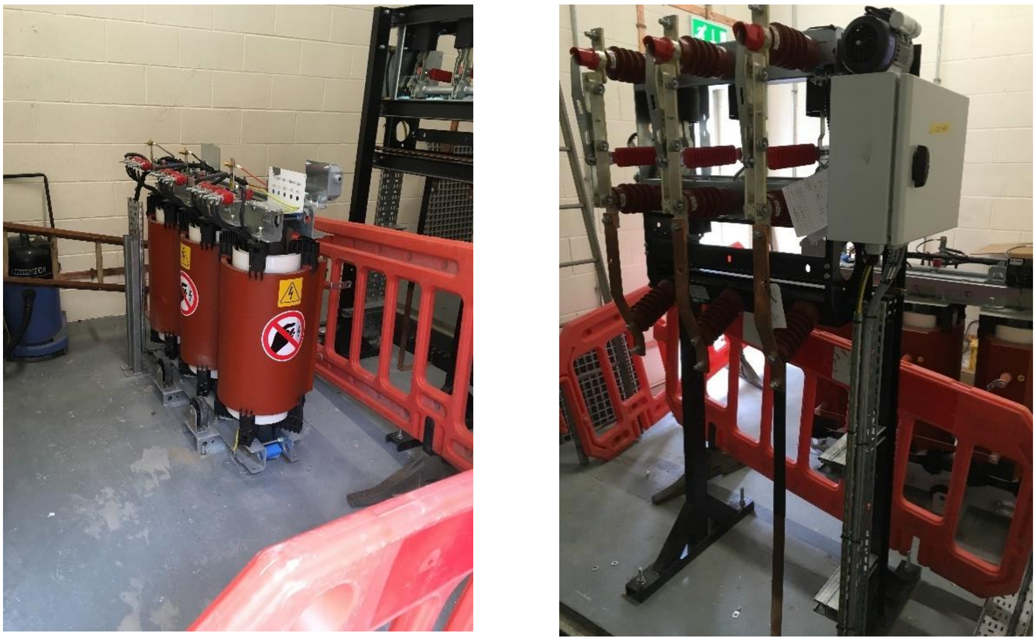


Figure 12 Single Line Diagram of Pre-Charge Unit consisting of the disconnector and exciter transformer.

The pre-charge disconnector and the exicter transformer were both dropped at the rear double doors of the building using a telehandler. The exciter transformer was moved into location using the wheels attached to the unit. Once in location the exciter transformer was secured in place with the frame bolted to the floor of the valve hall. The disconnector was moved into location using skids. Once in the correct location, it was secured in place with the frame bolted to the floor. With both components in place this concluded the mechanical installation of the pre-charge unit, with both components shown in Figure 13.



(a) (b)

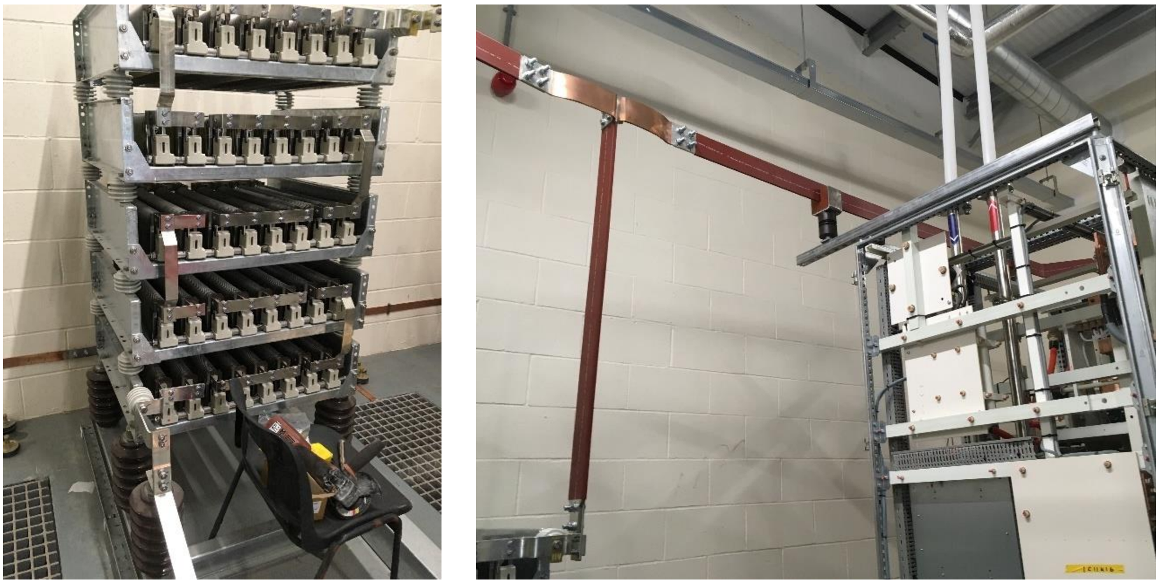
Figure 13 (a) Photograph of the Pre-charge unit Exciter Transformer installed. (b) Photograph of the Pre-charge unit Disconnector installed

Following mechanical installation, the LV supply cable from the LV distribution board was connected to the LV input terminal flags of the exciter transformer using cable lugs and bolts. The connections between the exciter transformer and the disconnector where also terminated. The output cables of the pre-charge unit were connected to the AC side of one of the inverter modules. Finally, earthing connections were terminated to both the exciter transformer and disconnector.

3.6. Grounding Resistor

The grounding resistors provide a ground reference for the inverter system and is intended to carry limited current for a short duration under fault conditions.

The grounding resistor was moved into the building using a telehandler through the rear double doors of the building. The grounding resistor was delivered with the post insulators and frame connected. The unit was then moved into its final position using a pallet truck and secured in place with bolted connections at the four corners of the steel frame. This concluded the mechanical installation of the grounding resistor



(a) (b)

Figure 14. (a) Grounding resistor installed within the valve hall including post insulators and frame. (b) Common connection of Inverter DC busbars to Grounding resistor HV terminal.

Following mechanical installation the DC busbars from the first inverter module were connected to the HV connection of the grouding resistor. The positive and negative pole inverter modules share a common connection to this point shown in *Figure 14* (a). The earthing connection was terminated on the grounding resistor's LV connection. Both connections were made using terminal flags and bolts. Finally, the ground resistor current sensor cable was connected to ensure any current is detected in case of a fault during operation.

3.7. Control Cubicles

The control cubicles installed within the control room are critical for the operation of the inverters and for controlling power transfer in the system. The control cubicles receive and process signals from the system's measured variables. These along with system set points are used to control the operation of the MVDC system. The inverter control systems at Llanfair and Bangor are connected via an optical fibre link. At each converter station the individual equipment control systems are hard wired to the control cubicles situated in the control room.

Each of the control cubicles were transferred to the building using a telehandler. The cubicles were moved into their final location using skids through the building's side double doors. Finally, the control cubicles were secured to Unistrut which was installed on the control room wall.

Figure 15 MVDC Station control panel showing HMI screen.

Following mechanical installation, the control cables from each of inverter station equipment was terminated within the cubicles. This included transformer monitor signals, DC switchgear status, pre-charge unit status, UPS feed output, heat exchanger and cooling fan controls.

3.8. LV Motor Control Board

The LV control board provides a LV supply to the cold-water pumps, cooling fan motors , pre-charge unit, UPS equipment and the DC switchgear. This connection ensures successful energisation of the MVDC link.

The LV control board was transferred to the building using a telehandler. The board was moved into its final location using skids through the building's side double doors. Finally, the LV board was secured to Unistrut which was installed on the control room wall.

Following mechanical installation, the input from the SPEN 400V LV distribution board was terminated in the LV control board. The output cables for the equipment described previously were also terminated within the board.

3.9. Primary Cooling System

3.9.1 Heat Exchanger

The heat exchanger system ensures that the heat generated by the inverter modules can be efficiently removed from the building allowing the inverters to function correctly.

To remove the heat effectively, the heat exchanger has a capacity of 451kW and transfers the heat using a medium consisting of 30% Monoethylene glycol and 70% demineralised water. The exchange surface area is 1843m^2 to ensure sufficient heat exchange. There are 8 axial fans with a 900mm diameter and a maximum speed of 930rpm that are used to transfer the exchanged heat into the surrounding air. The heat exchange medium is circulated using pumps located in a pump skid.

The heat exchanger is located on a gantry above the pump skid as seen Figure 16.

Figure 16 Heat exhanger located on gantry above the pump skid

3.9.2 Pump Skid and Cooling Fans

The pump skid and heat exchanger were located using a crane with a controlled lifting plan in place. Steel cross beams on the gantry were removed to lower the pump skid into place and replaced after lifitng was completed. The pump skid was bolted into place on the concrete plinth. The heat exchanger was lifted and lowered into position, followed by secure connection to the gantry.

Following mechanical installation the cold water and heat exhange pipes were connected between the pump skid and heat exchanger. Pipes were passed through ducts in the building walls into the converter hall with the ducts sealed following installation. Control and LV supply cables were pulled through ducts from the building and terminated in both the heat exchanger and the pump skid. LV cable connections between the LV control board and the cooling fans and pumps were established. Finally, control cable connections between the cooling fans and control cubicles were established.

(a)

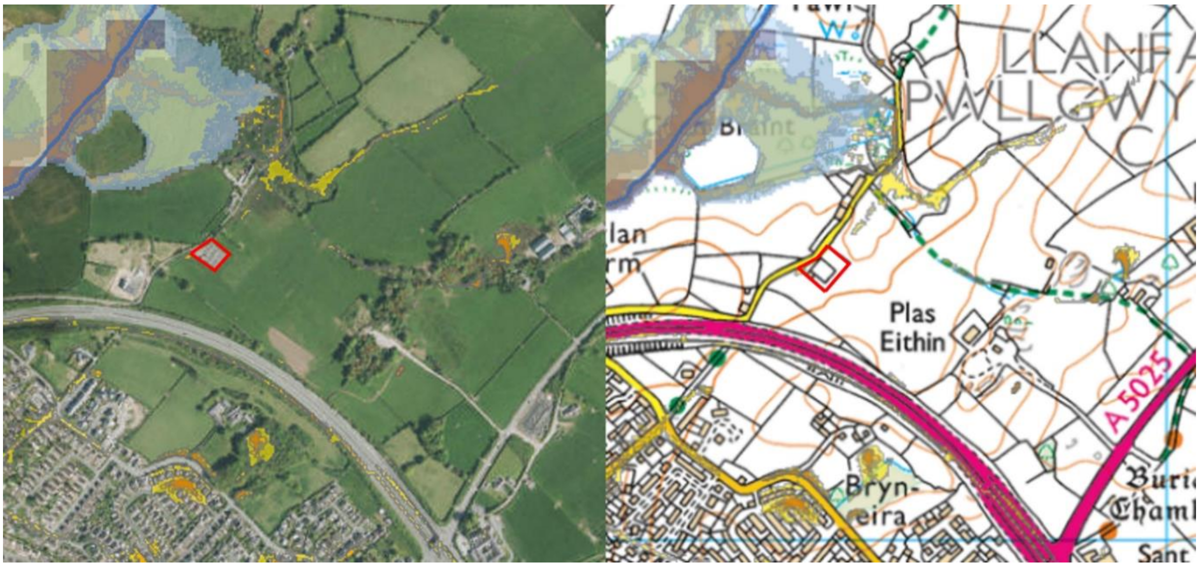
(b)

Figure 17 (a) Pump skid installed with pipes to heat exchanger and valve hall shown.(b) Heat exchanger installed with control and supply cables connected.

SECTION 4 CONSIDERATIONS FOR FUTURE INSTALLATIONS

4.1. Site Flood Risk

The internal converter station environment requires temperature, humidity and dewpoint control to avoid moisture damaging the semi-conducting equipment. Therefore, building water ingress must be prevented over the lifetime of the converter stations. Before construction, the Project consulted Natural Resource Wales (NRW) flood hazard and risk maps for the MVDC supplier tender process, which showed less than a 1% (1 in 100 year) chance of flooding risk from surface water, rivers or the sea as shown in Figure 18. The effects of a warming climate are considered in the calculation of the risk bands in the NRW model.



Key:

Risk of Flooding from Surface Water

High –

Med –

Low –

Risk of Flooding from Rivers and Sea

High –

Med –

Low –

Very Low –

Figure 18. Long terms flood risk map for Llanfair PG Converter station site, showing flood risk from surface water, rivers and the sea. The substation site boundary is shown in red.

In addition to the desktop assessment, detailed ground investigations were carried out at each site. These assessments measured the soil permeability in the field, using in situ borehole permeability testing techniques at one location at each site. The Llanfair PG basic infiltration rate result was high and consistent with sandy soils, meaning water should drain away relatively quickly.

In February 2020, following the completion of the building works, the UK experienced the wettest February on record, with Anglesey experiencing twice the average rainfall for this month. The project completed the ground works and construction works before the heaviest rainfall period, so the construction works were largely unaffected by local surface water flooding.

Since completion, the area has suffered from a high-water table and surface level flooding, with only moderate rainfall despite the high soil infiltration rates measured before and during construction. This high-water table poses an operational risk, due to multiple points of cable entry below ground level into the internal cable trenches. To mitigate this risk, the cable ducts have been sealed with high quality, durable cable seals to prevent water ingress into the cable trenches. Trench puddle pumps and water detection alarms have been fitted in trench sumps to detect water ingress at the earliest opportunity. Further measures are recommended for future projects, due to the trend in increasing rainfall across the UK due to climate change.

4.1.1 Flood Prevention Recommendations

Recommendation 1 – Pre-construction long term ground water monitoring, at multiple locations per site, should be adopted as standard for MVDC converter station to ensure the flood risk is lowered as far as possible through the site civil design.

Recommendation 2 - The building installation height is usually a concern from a planning perspective. This can incentivise civil design engineers to lower cable entry pits and trenches below ground level, which is standard practice. For converter stations however, internal trenches could be raised above ground level at sites with a high ground water level to ensure the risk of water ingress is minimised further.

4.2. Maintenance

Much of the maintenance requirement of the converter stations is similar to that of a conventional substation. The majority of equipment will require visual checks, checks and correction for loose connections and cleaning of surfaces, contacts and connections. Maintenance will occur periodically based on manufacturers recommendations as well as after any fault conditions within the system. The areas in which there are differences in maintenance requirements are the inverter modules, control system and secondary cooling system.

4.2.1 Inverter Modules

The inverter modules will require periodic checking of the sensitive power electronics and various connections, ensuring these surfaces are free from dust particulates and there is no evidence of electrical arcing. Particular attention will be given to checking for the presence of water that may drip onto the modules from moisture collecting on surfaces above the modules within the valve hall. Any checks with in the valve hall will require a shutdown lasting at least several hours at each site. Shutdowns for visual inspections could be reduced by installing high resolution cameras within the valve hall.

4.2.2 HVAC Secondary Cooling system

The presence of a Heating Ventilation and Air Conditioning (HVACs) system for internal environmental control, within a DNO substation, is unusual. The HVAC system uses compressors and pumps to cool and drive the coolant between the outdoor heat exchangers and internal Air Conditioning (AC) units. As compressors and pumps are moving parts, or are under cyclic stress, they are prone to wear and require high availability of spare parts with regular replacement. As the HVAC system is a closed system, the air change rate is low, but filters for the incoming air supply and valve hall air conditioning units will require periodic inspection and replacement.

An alternative open system design would not require a chiller with pumps, as the heat from the converters would be blown out of the valve hall by a large building supply fan. This method requires very large building air change rates and would require larger air supply filters, with more frequent replacements, to ensure the internal environment is from dust and particulates.

4.3. Building Construction

The Angle-DC project used standard substation construction techniques, which were modified to improve the internal building environment typically found in substation buildings. These modifications were namely the HVACs system and building air tightness. The building design uses a trenched concrete base to support a rigid steel frame, which in turn supports an insulated sheet steel roof. The sides of the buildings are enclosed with an insulated cavity wall. The entire volume of the enclosed building is conditioned by the HVAC system.

To save on building excavation and material costs, an outdoor design for the converter modules is possible, though some development by MVDC converter suppliers would be required. An outdoor design would have the advantage having of having weather proofed modules, within a much smaller enclosed volume, requiring smaller and less expensive HVAC systems. Concrete bases and trench formwork would still be required, but the foundation volume would also be reduced in the absence of an enclosing building.

SECTION 5 ACCURACY ASSURANCE STATEMENT

The Project Manager and Director responsible for the 'NIC – Angle-DC Project' confirm they are satisfied that the processes and steps in place for the preparation of this Project Progress Report are sufficiently robust and that the information provided is accurate and complete.

Signature (1): James Yu – Future Networks Manager