INITIAL DESIGNS FOR ANGLE-DC PROJECT: CHALLENGES CONVERTING EXISTING AC CABLE AND OVERHEAD LINE TO DC OPERATION

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ABSTRACT

This paper describes the initial development work and first year challenges for the ANGLE-DC project; an innovative proposal to convert two existing AC circuits, from the island of Anglesey to the Welsh mainland, to operate as DC circuits. This project was proposed under the 2015 Network Innovation Competition organised by Ofgem.

At present there is a double-circuit 33kV AC connection between the Llanfair-PG and Bangor sub-stations. Each 3km circuit consists of a short section of overhead line, with the majority of the circuit length being underground cable. The project will demonstrate the use of existing circuit assets operating under DC stress in a coastal location.

The DC voltage will be ±27kV, with a DC current rating of 556A; providing a 23% increase in transmitted power capacity, from the existing operational limit of 24.8MW to 30.5MVA.

1 INTRODUCTION

The electrical power distribution networks in the South of Scotland, North Wales and the North-west of England are provided by Scottish Power Energy Networks (SPEN). When considering the future development of their distribution networks, SPEN identified a number of network challenges which would need to be overcome:

- Increasing demand growth due regional redevelopment on Anglesey and the build out of the Horizon nuclear power station;
- The doubling of connected Distributed Energy Resources (DER) by 2020, placing pressure on the distribution network in terms of voltage profile management and thermal limits on circuits and transformers;
- The creation of new way-leaves for additional distribution circuits and substations is difficult in the UK; and
- A passive distribution network does not satisfy future network requirements.

To address these issues, SPEN proposed the deployment of Medium Voltage Direct Current (MVDC) technology, which could embed a link with controlled power flow within the distribution network. Such a link could enable power and voltage control over a wide area of influence within the network, increase the capacity of an existing circuit and actively control the power through the link. The project, called ANGLE-DC, was submitted to the UK Office of Gas and Electricity markets (Ofgem) under their 2015 Network Innovation Competition (NIC) and received funding to enable the project to start in January 2016 [1].

This paper details the initial development work and challenges for the ANGLE-DC project. Section 2 provides a general overview of the project. Section 3 discusses approaches taken and challenges involved converting the AC circuit to DC operation. Section 4 outlines the suitable candidate DC technologies and general requirements. The back-up circuit and sequence of DC circuit energisation are discussed in Section 5. The main project outcomes and conclusions so far are presented in Sections 6 and 7.

2 PROJECT DESCRIPTION

Anglesey is located of the north coast of Wales, separated from the mainland by the Menai Strait, as shown in Figure 1.

Figure 1. Island of Anglesey in north Wales. Image courtesy of Map data © 2016 Google.

In the Anglesey area, the volume of DER and the demand for electricity are increasing significantly. The demand growth forecast for this area is around 11%, reaching 81 MW by 2023 [2]. The connected and contracted DER connections have reached around 150 MW. Consequently, voltage and thermal rating issues in several locations in Anglesey and North Wales need to be addressed. Additional headroom derived from increased capacity of circuits operating using DC will bring benefits to the wider area and reasonable provision for uncertain future developments.

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

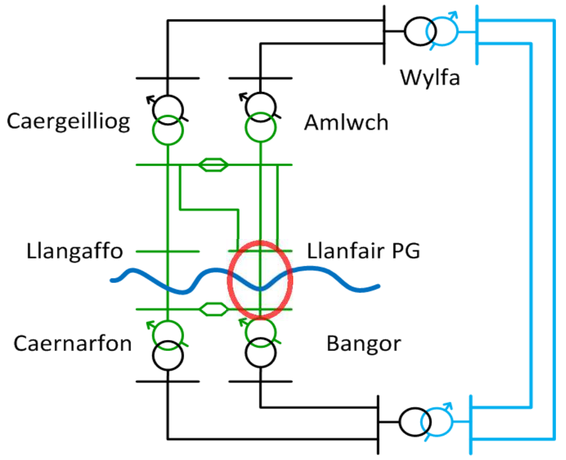

Figure 2. A simplified interconnection diagram showing the MVDC link location within the network. 400 kV – blue, 132 kV – black and 33 kV – green.

The circuit from Bangor (mainland) to Llanfair PG (Anglesey) was identified as a suitable location for the MVDC demonstration project. As shown in Figure 3, the circuit consists of a short section of 33kV overhead line, close to Llanfair PG sub-station, with the majority of the route being underground cable. The total route length is about 3km, with about 450 m of the cable crossing the Britannia bridge lower deck, which carries rail traffic in close proximity to the MV circuit cables.

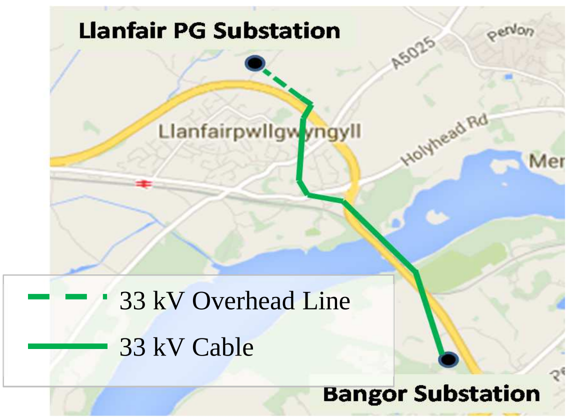

Figure 3. Original Llanfair PG to Bangor AC circuit.

The use of DC technology will bring a number of benefits to the operation of the distribution network and hence to the consumer:

- Enhanced power flow through an existing circuit;
- More precise control of the flow of power in the distribution circuit;
- No possibility of overload of the circuit;
- Control of voltage at either end of the distribution circuit, including STATCOM mode for long outage periods;
- Control of reactive power flow at both ends of the distribution circuit;
- Lower losses in the wider distribution network due to the improved voltage and power flow control;
- Rapid support to the system voltage during faults;
- Fault level decoupling between distribution systems;
- Potential to integrate the controllers of the DC link into wide area monitoring and control systems; and
- Facilitating accelerated access to the network for renewable connections.

3 AC TO DC CIRCUIT CONVERSION

The existing 33kV Llanfair PG to Bangor AC circuits are shown schematically in Figure 4 and consist of two three-phase circuits operated in parallel, via a single circuit breaker at each end.

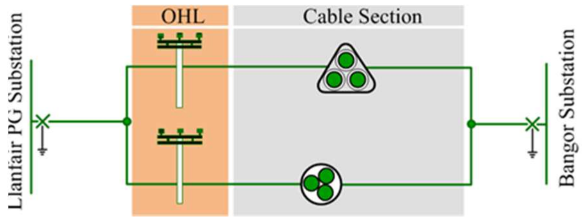

Figure 4. Existing AC circuit showing simplification of circuit construction types along route.

Each circuit has multiple sections, with several designs of cables being used, each with different insulation systems. The cables were originally installed in the 1960's, with some sections replaced with more modern designs. The age and the insulation systems used in the sections of the cable circuit have an impact on the choice of DC voltage and current, as discussed in Section 4.

For the conversion to MVDC operation, AC to DC converters will be installed at both sub-stations, via suitable interface transformers, as shown in Figure 5.

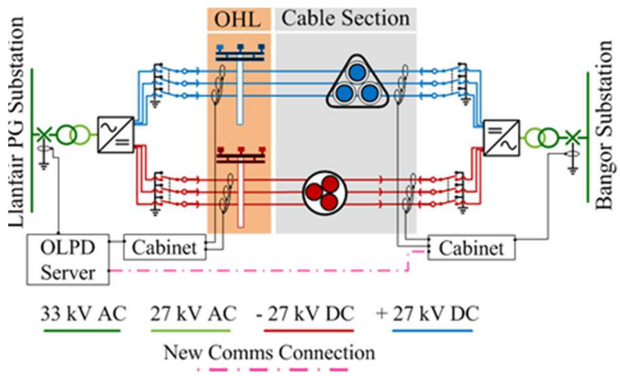

Figure 5. The new DC circuit with an Online Partial Discharge monitoring system and new communications connection.

As indicated in Figure 5, the 3 conductors of each AC circuit will be grouped to form the positive and negative conductors. A manual disconnector, with incorporated grounding switch, will be installed to provide isolation of the DC circuit for testing and maintenance. A single phase fault on one of the DC cables can be isolated from the circuit, using portable grounding to allow cable repair, while the remainder of the circuit is returned to service. A cable from the other polarity can be removed from service to balance the DC resistance of the positive and negative conductors, allowing DC link operation at 67% of its power capability until the cable repair is completed.

When considering the re-use of the existing AC assets, the overhead lines and particularly the underground cables, the values of two key parameters needed to be resolved, i.e. the choice of DC voltage and current. The cables presently experience a peak phase to ground voltage equivalent to

$$V_{peak} = \sqrt{2} \text{ x } 33\text{kV}/\sqrt{3} = 27\text{kV}. \qquad (1)$$

Although the cables are rated at 36kV, a prudent approach has been adopted, using the peak phase to ground voltage of ±27kV as the design voltage for the ANGLE-DC project.

To establish the DC current rating, analysis of the AC cables types were used. Three designs are present:

A - H paper oil rosin insulation, 3-core design;
B - HSL impregnated paper insulation, 3-core design; and
C - XLPE insulation, 1-core trefoil design.

As type A represented the longest and oldest sections of cable, this becomes the limiting factor when considering the thermal duty on the cables. At present, the cables are operated at a current of 217A, which gives an insulation temperature of 65°C. However, it was decided to limit the temperature of the insulation to a conservative figure of 50°C and a current of 188A per core was chosen, i.e. a DC rated current of 564A. Thus the notional power rating of the ANGLE-DC scheme was chosen as,

$$P_{dc} = 2 \text{ x } 3 \text{ x } 27\text{kV x } 188\text{A} = 30.5\text{MW} \qquad (2)$$

This compares with the power rating available for the 2 circuits under AC operation, which is

$$P_{ac} = 2 \text{ x } \sqrt{3} \text{ x } 33\text{kV x } 217\text{A} = 24.8\text{MW} \qquad (3)$$

A key facet of the ANGLE-DC project is the demonstration that the existing AC distribution assets can be retained and operated under DC conditions. Despite the conservative current and voltage ratings, it is recognised that the impact of a constant DC stress is different to the time varying stress experienced under AC conditions and typically outdoor insulation would require longer creepage distances for DC applications than for AC application.

3.1 DC Creepage

The two overhead lines use porcelain line support insulators, which have a creepage distance of ~ 900 mm, i.e. 47mm/kV based on the nominal rms voltage. For operation under DC stress, the creepage distance will be 33.3mm/kV. This may be increased to 50mm/kV should the nominal 27kV DC voltage cause issues during the commissioning stage.

The proximity of the overhead line to the coast introduces the possibility of saline pollution on the insulators which, in the presence of moisture, could lead to leakage current across the insulators or in the worst case flash-overs. Part of the learning exercise of the project is to monitor the behaviour of the line insulators, under DC stress conditions, to assess their suitability for long term operation. Enhanced measures, such as the application of grease, the use of additional sheds or replacement with units of longer creepage distance or by polymeric insulators may be required.

3.2 Electromagnetic Compatibility

The lower deck of Britannia Bridge supports two rail tracks which contain various utilities, including the two 33kV power cables. One track is out of use and houses the 3 XLPE single cores within a concrete trough (pictured in Figure 6). The occupied track supports the HSL 3-core cable, which is ~5.4 m from a Network Rail signal cable. In DC operation, the positive and negative circuit cables will lie ~ 5.3 m apart from each other.

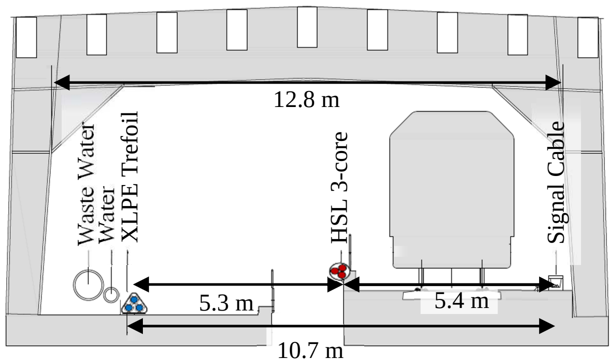

Figure 6. Steel cross section of the Britannia Bridge lower rail deck showing cable spacing and distance from signal cable.

In a purpose built DC cable design, the positive and negative poles would be located immediately adjacent to each other. Any time varying magnetic fields caused by positive and negative sequence harmonic currents would almost exactly cancel, minimising the risk of inducing currents in nearby conductors.

The physical arrangement of the DC poles in relation to the signal cable represents another unique learning opportunity for the project in the form of Electromagnetic Compatibility (EMC) between MVDC distribution circuits and rail infrastructure. The EMC problem on the bridge stems from the fact that XLPE pole will be twice the distance from the signal cable than the HSL pole, minimising any cancellation of time variant magnetic fields. Other DNOs are unlikely to encounter a more problematic MVDC pole arrangement in such close proximity to trackside equipment.

Through early dialogue with Network Rail, SPEN have begun a 2-part Common Safety Method Risk Assessment (CSM RA) based on EU Commissioning Implementing Regulation 2015/1136 and Network Rail's company standard [3]. The purpose of the CSM RA will be to achieve functional safety when the DC link and Network Rail's active safety systems are in operation. This will be the first CSM RA to cover MVDC distribution circuits anywhere in Europe. HVDC projects have previously studied EMC between HVDC cables and smart road infrastructure [4].

SPEN Engineers have carried out harmonic impedance tests, up to the 40th harmonic, on each 33 kV cable. These results will be used to estimate the levels of positive, negative and zero phase sequence harmonic currents on the Britannia Bridge, which will be used by EMC modelling specialists to calculate the interference caused by the DC link.

The first part of the CSM RA will take place in Q1 2017 and will identify the safety measures needed for the conversion to DC. These measures may be additional harmonic filtering on the DC circuit or changing the IGBT switching frequency to shift DC harmonic currents to minimise coupling. Another alternative would involve grouping 2 cables from one circuit with 1 cable from the other to improve cancellation of time variant magnetic fields. The benefits and potential risks of this arrangement, shown in Figure 7, will be assessed.

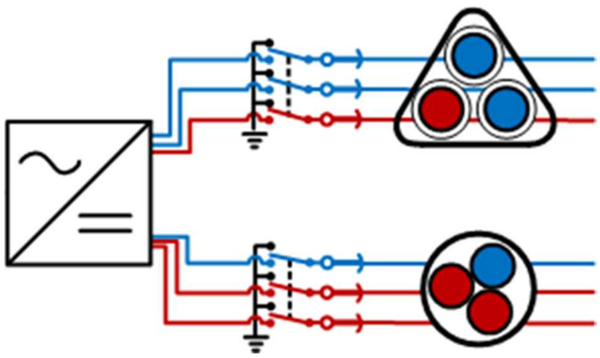

Figure 7. An alternative conductor arrangement, with red as minus 27 kV and blue as plus 27kV.

The second part of the CSM RA will take place during commissioning in Q1 2019 and is intended to deliver EMC design confidence through engineering acceptance (compliance with Railway Group Standards) and an EMC safety submission (e.g. testing to BS EN 50121 & 50122). BS EN 50121 does not cover harmonic currents less than 150 kHz, induced currents or testing under fault conditions, so new testing techniques will need to be developed. The testing must allow for all modes of DC converter operation and the physical ageing of equipment over the 20 – 30 year lifetime of the DC link. Once the CSM RA has been concluded, it can be used as a reference case for future MVDC links, reducing risk and uncertainty in future projects close to rail infrastructure.

3.3 Holistic Condition monitoring

The impact of DC stress on the different types of cable, currently in use on the link, will be monitored to assess whether this induces Partial Discharge (PD) within the insulation. Partial Discharge is a time dependent phenomenon, occurring within voids in solid cable insulation. It is unclear what effect the application of a constant DC stress will have on voids within the cable insulation.

Initial testing of the cables was undertaken at a DC voltage of 38kV (40% above the design DC voltage) and minimal levels of PD were recorded. As part of the ANGLE-DC scheme, an On-Line PD (OLPD) monitoring system will be installed at each end of the link, as indicated in Figure 5. This will provide a real time view of the level of PD within the cables to assess whether the DC stress is causing any long term degradation. The DC PD data will be logged to allow benchmarking with the AC PD data; AC and DC PD trending of the cable insulation will be compared and published.

The on-line monitoring 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.

4 MVDC TECHNOLOGY

Due to the unique nature of the ANGLE-DC project and the potential for future such links in the UK distribution networks, the choice of technology of the MVDC scheme is being left open to suppliers. Thus designs based on HVDC, STATCOM, transportation power supplies and industrial drive solutions will be considered. The main imperative for the chosen technological solution is that it meets the functional requirements of the scheme, which are:

- An economic solution which can be utilised in future projects;
- Meets the required power transfer capability and is capable for use on schemes of higher powers;
- Meets the required DC voltage capability and is capable for use on schemes of higher voltages;
- Provides independent reactive power control capability at each end of the link;
- Provides high operational reliability;
- Operates with low power losses;
- Is capable of un-manned operation;
- Operates with acceptable power quality parameters; and
- Has minimum environmental impact.

The supply of the converter equipment is the subject of a competitive tendering exercise. The successful bidder will work with SPEN and its consultants to develop the detailed designs of the project.

5 PROJECT EXECUTION PLAN

SPEN has developed a strategy to minimise the risk to the electricity supply to consumers during the conversion stage. This will involve the installation of an additional 33kV AC circuit between Llanfair PG and Bangor substations. Figure 8 shows the sequence of installation and commissioning, prior to the conversion works on the existing circuits.

This new AC circuit forms an integrated part of the project to enable outage of the DC circuit for commissioning, testing and optimisation of the power flow control between the AC and DC circuits; it will not be needed for future business as usual deployments of MVDC technology.

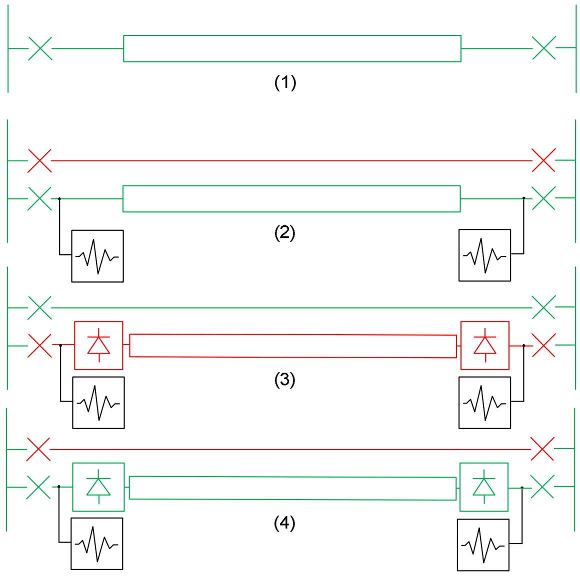

Figure 8. The sequence of DC circuit energisation. Green – In operation, Red – Out of Service. (1) Initial condition. (2) Construction of new AC circuit and commissioning of OLPD system, June 2017. (3) New AC circuit commissioning, Q4 2018. (4) Commissioning of MVDC converters, Q1 2019.

6 OUTCOMES OF THE PROJECT

The successful implementation of the ANGLE-DC project will demonstrate the benefits of DC technology and will represent a significant step forward in the deployment of DC technology in distribution systems. The project will develop a number of key features which will be important for the future up-take of MVDC technology:

a. The successful conversion of AC assets to DC operation. This includes overhead lines in a potentially (saline) polluted environment and underground cables of different insulation systems and ages;
b. The entrance into the MVDC market of new suppliers and of technologies which may come from business sectors outside of power transmission;
c. Technical solutions with an economic basis which is appropriate for distribution systems. This includes the initial capital expenditure (CAPEX) and also the on-going operational expenditure (OPEX);
d. The identification future opportunities for the deployment of MVDC technology to overcome operational issues in distribution networks;
e. The dissemination of the knowledge gained during the project execution and the first year of operational service.

In relation to item d), SPEN identified 20 – 25 possible locations where MVDC links could bring real added value to the operation of the networks, suggesting a future market for this type of technology.

7 CONCLUSIONS

The development of the ANGLE-DC project represents a significant step forward in the deployment of power electronic technology in the distribution networks. By introducing AC – DC converters into the network, an increase in the power flows can be achieved whilst retaining the existing distribution assets.

A cautious approach has been adopted in the choice of DC voltage and DC current, recognising the risks of over-stressing the existing overhead lines and underground cables. However, this retention of the existing assets represents one of the main innovations of ANGLE-DC.

A condition monitoring system will be installed to provide a real time view of the levels of PD in the circuit to monitor the long term health of the system and warn of any incipient faults.

Recognising the inherent risks to electricity supplies to consumers on the island of Anglesey from such an innovative project, a standby AC circuit will be installed as part of the overall project.

A key feature of the project is the learning gained during the design, commissioning and construction phases and the first year of operational experience. These learning outcomes will be shared widely with all of the stakeholders in the project.

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