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Planning and implementation of an HVDC link embedded in a low fault level AC system with high penetration of wind generation

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SUMMARY

There is a need for new power transfer corridors, especially in mature networks such as in Europe and North America, to accommodate the increased development of renewable generation. However, the licencing process to authorise the construction of new overhead lines is complicated and there is a risk that it may be impossible to get planning permission. Where the option exists, alternative schemes based on subsea cable and HVDC technology can offer network reinforcement more quickly as a result of reduced planning timescales.

In the north of Scotland, Scottish Hydro Electric Transmission (SHE Transmission) had a requirement to reinforce the transmission system in Caithness to accommodate the export from Caithness of increasing volumes of wind generation. In this case there were both onshore AC overhead line and subsea HVDC transmission reinforcement alternatives. An assessment of options taking into account environmental impact, cost benefit analysis (CBA) and system performance recommended the subsea HVDC approach. The link was commissioned at the end of 2018 [1].

The low fault level conditions in Caithness prompted the selection of Voltage Source Converter (VSC) technology for the Caithness-Moray (CM) HVDC link. As well as the fundamental export capability, the VSC link provides valuable system support, such as through its reactive power capability including voltage control, black-start capability, and island mode operation. The VSC technology also enables the potential to tee-in a future multi-terminal connection to Shetland.

The HVDC link operates in parallel with the existing onshore AC system. That parallel AC system however only comprises a double circuit 275kV overhead line route and a double circuit 132kV overhead line route – hence the original requirement for reinforcement. In the event of depletion of the AC system through a combination of credible AC fault and pre-planned AC system outage, the 800 MW DC link could suddenly be left in parallel with two much lower capacity 132kV circuits on an AC system with a much-reduced fault level.

HVDC circuits, unlike AC circuits, rely on pre-programmed control actions for a response to changed conditions in the AC network in which it is connected. Three key controls were therefore

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studied, simulated in both time-domain and real-time environments, and implemented in CM HVDC link control to ensure an appropriate response to sudden depletion of the parallel AC network.

The Caithness-Moray HVDC link has been designed as a five terminal HVDC system, including the detailed design of three converter stations, an HVDC switching station and a DC Grid Master Controller. During the detailed design, multiterminal studies were conducted with the complexity of different modes of operation for the multiterminal HVDC system. Rating studies and performance studies were undertaken with Electro-Magnetic Transient (EMT) simulation program using a virtual control system, which uses the actual control software to be delivered together with the consideration of the latencies as introduced by the hardware in the real system, and thereby made it possible to verify the performance in the study phase instead of later in the project during the Factory System Test (FST).

This paper describes transmission investment planning CBA considerations, the planning study of the network in the Caithness area and the design of the multiterminal HVDC system.

KEYWORDS

Transmission system reinforcement - Cost Benefit Analysis - Weak network - Low fault level AC network - multiterminal - Factory System Test - Emergency Power Control - DC switching station - DC grid master controller

1. INTRODUCTION

The purpose of the Caithness-Moray Transmission project is to strengthen the power transfer capability from Caithness in the far North of Scotland down to the Moray area, transmitting the renewable power production which has been growing rapidly in recent years from the development of wind power generation in the Caithness area.

In addition to the fore-mentioned demand, there was a requirement for fast delivery and low environmental impact of the network strengthening, and a need for reactive power compensation and flexible voltage support for the low fault level AC network in Caithness.

2. PLANNING OF THE CAITHNESS-MORAY TRANSMISSION PROJECT

2.1 Investment planning

Scottish Hydro Electric Transmission plc (SHE Transmission) is the owner and operator of the electricity transmission system in the north of Scotland. SHE Transmission’s obligations under the terms of its transmission license awarded by UK national regulatory authority OFGEM (Office of Gas and Electricity Markets), include the development of an economic, efficient and coordinated transmission network. The rapid growth of renewable generation in the Caithness area in excess of existing transmission export capacity required SHE Transmission to identify and assess network investment proposals.

The two main reinforcement options were re-building existing onshore AC 132kV overhead line routes to 275kV down the eastern coast line of Caithness, or the establishment of an HVDC subsea link across the Moray Firth, see figure below.

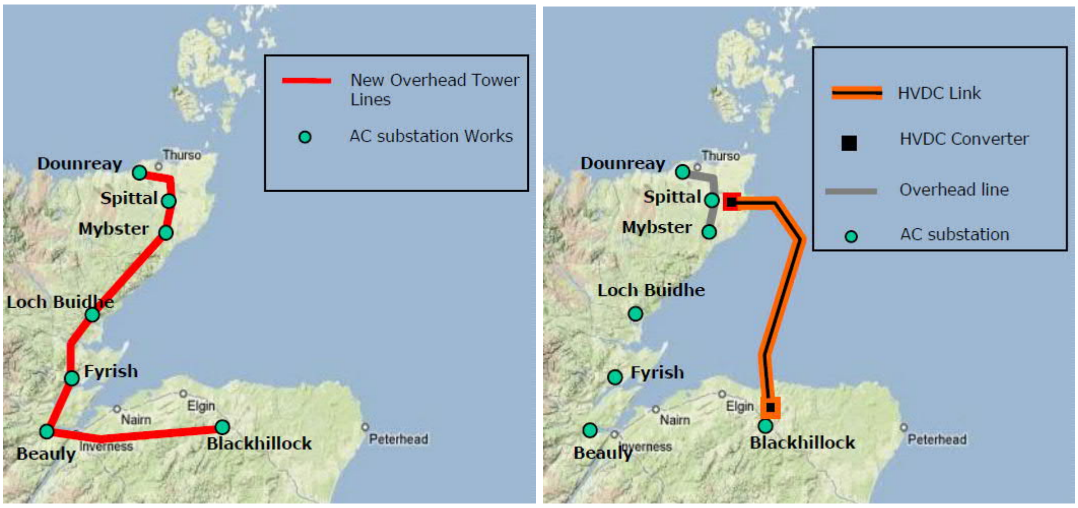
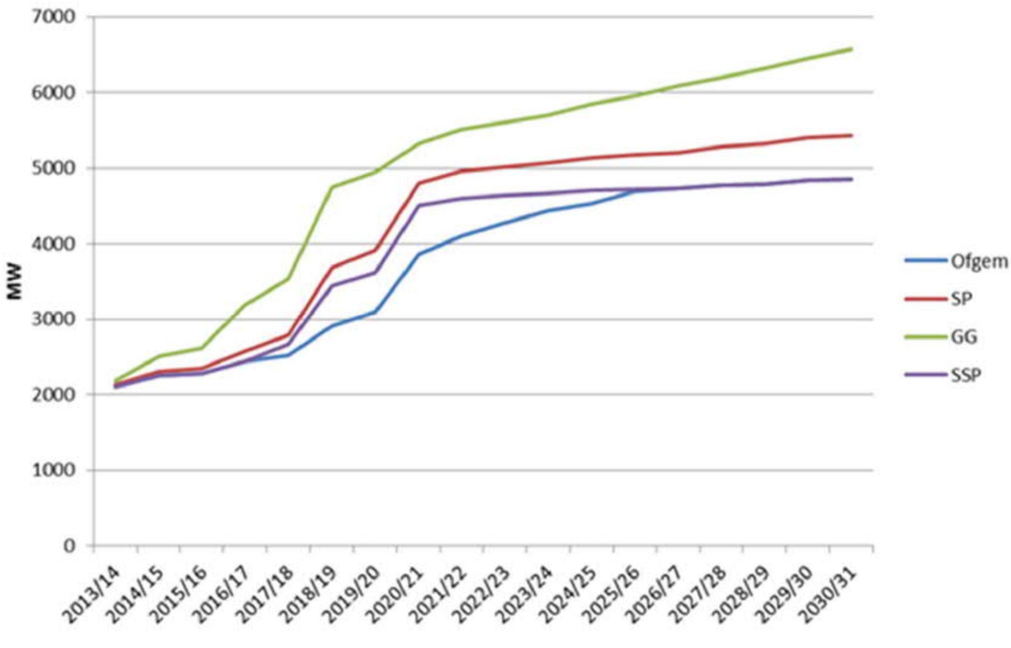


Figure 1. The two main options for transmission reinforcement.

A Cost Benefit Analysis (CBA) was conducted by SHE Transmission during 2012-2014 for the investment proposals, calculating the Net Present Value (NPV) of the different reinforcement options for a period of 40 years and for three main generation scenarios:

1. Slow Progression (SP), based largely on known renewable development projects,
2. Gone Green (GG), where the rate of renewable growth is optimistic, yet achievable, to put UK in a low carbon economy,
3. Slower Slow Progression (SSP), with a slower growth than "empirical evidence indicates".

In addition to the three above, OFGEM added a fourth CBA case, (Ofgem/Reduced Deployment (RD)), where there is a slower renewable growth than SSP up to 2020, then keeping that growth until 2026/2027, where SSP levels are reached see the figure below.



Source: SKM

Figure 2. The four different generation scenarios for the renewable growth in northern Scotland.

Dynamic constraint cost approach was used with constraint costs ranging from £95/MWh to £130/MWh, with an average of £123/MWh.

In the following table, the net consumer benefits are shown, using the lower constraint cost of £95/MWh, a 4.6% Weighted Average Cost of Capital and 3.5% Social Rate of Time Preference, including a £100m cost reduction for the AC reinforcement alternative (based on reasonable possible cost cuts) and everything discounted over 40 years. Included is also Visual Amenity (VA) impacts for the AC transmission option. The table is discussed in greater detail in Ofgem's decisions letter of July 2014 [2].

Table 1. Net consumer benefits of reinforcement options

Option (£m, 2013 prices)	Generation Scenario			
	SP	GG	SSP	RD
AC transmission reinforcement with VA	1240	2195	285	298
AC transmission reinforcement without VA	1404	2359	449	462
DC transmission reinforcement	1340	2372	292	251

The table shows the DC transmission reinforcement winning out in CBA terms over the onshore solutions when monetised visual amenity is taken into account. In its letter of July 2014, Ofgem summarises its assessment and considerations that lead it to conclude that, "Overall, we think that the proposed solution (subsea HVDC) is likely to be in the interests of existing and future consumers."

In particular, it was recognised that risk of timely delivery was reduced with the subsea option with consequently reduced exposure for customers to costs of delay.

Additional technology benefits with VSC HVDC reinforcement were also identified during the assessment of the two options, such as the reactive power capability of the HVDC converter, voltage control, black-start capability, island mode operation and potential for a multi-terminal connection to the Shetland Islands.

Therefore, the benefits of early delivery for connection of renewables to limit carbon emission combined with low environmental impact and with the possibility of a multi-terminal connection to the Shetland Islands, made the DC transmission option preferable over the onshore AC transmission option.

2.2 Planning studies for very weak AC system

The CM HVDC link is "embedded", i.e. it is implemented within the same synchronous AC network and runs in parallel with the North-South AC transmission corridor (including double 275 kV and 132 kV circuits). The AC network surrounding the converter in the Caithness area, Spittal, during normal operation is not an electrically strong (high fault level) part of the system and under certain network conditions where there is a complete loss of 275kV continuity between Beauly and Spittal the fault level can drop considerably. The challenge in HVDC control terms was therefore to cover a wide range of potential fault levels, from very low potential levels under depleted system conditions to much higher levels in mid-term future under intact conditions on a further reinforced network.

Below is an overview of the AC network around and between the two converter stations, where the converter stations are encircled in green; Spittal in the Caithness area and Blackhillock in the Moray area, showing the main 275kV transmission corridor in red together with the 132kV connecting into Spittal station in black.

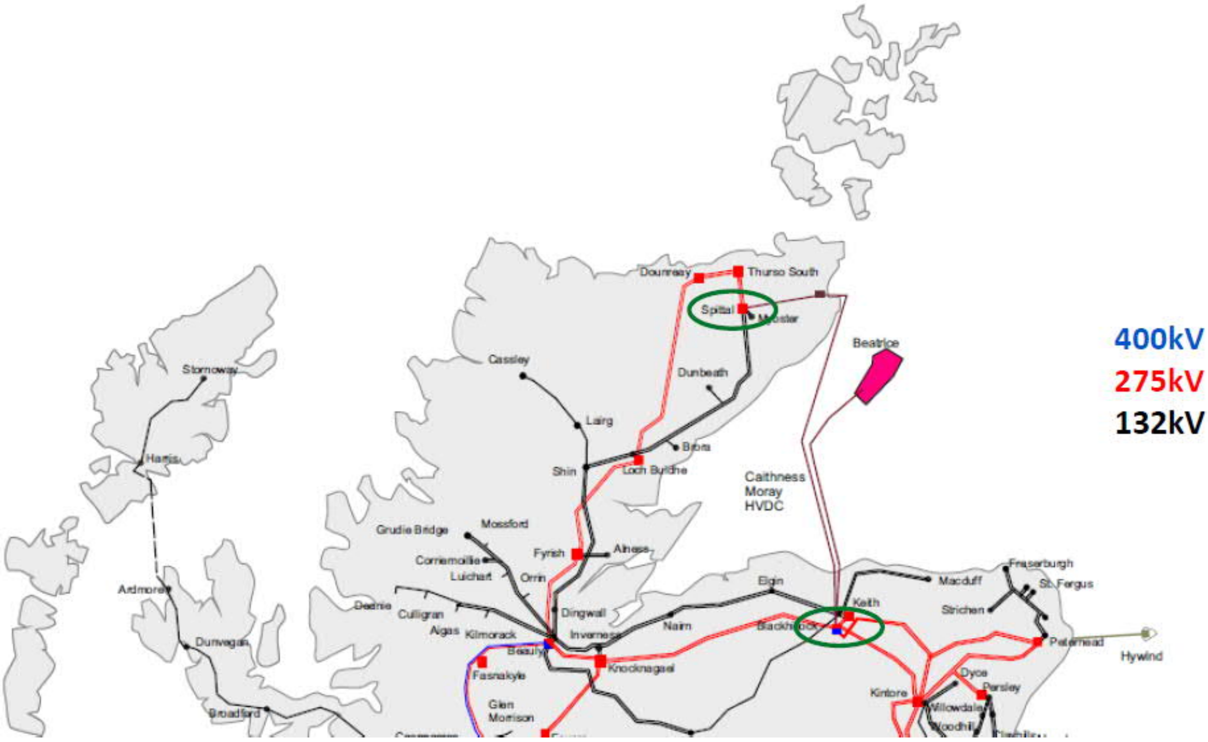


Figure 3. Overview of the 275kV AC transmission corridor in parallel with the CM HVDC link, together with the 132kV circuit. Both converter stations, Spittal and Blackhillock, encircled with green.

The normal power transfer, for both the 275kV AC transmission corridor and on the CM HVDC link, is from north to south due to the dominating on-shore wind generation in the Caithness area around the Spittal station. Depending on generation, CM HVDC link dispatch and the AC network topology there is a potential risk of overloads on the 132kV double circuits, PM1 and PM2, connecting into Spittal, see also Figure 4 below. This overload can range from marginal to severe depending on the system conditions.

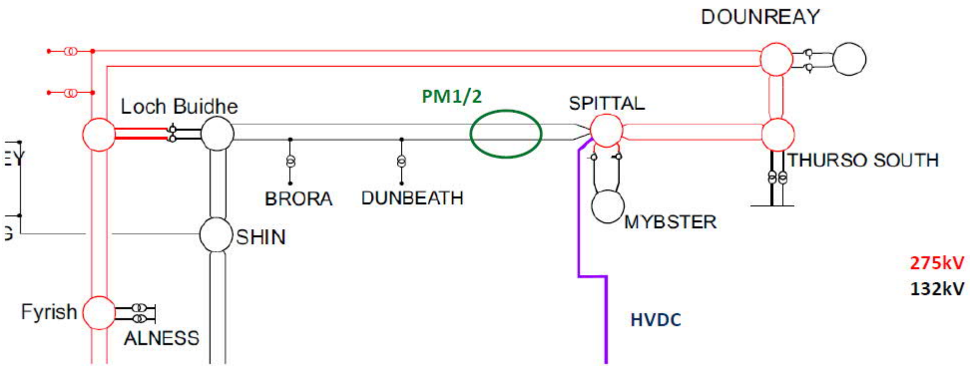


Figure 4. The 132kV double circuits, PM1 and PM2 connection into the Spittal station together with the 275kV double circuits transmission corridor, where the substations are marked as circles

In order to assess potential overloads and the dynamic performance in an electrically weak AC system (low fault levels under depleted conditions), extensive planning studies were done, e.g. load flow and dynamic studies. During these studies it was found that for the worst-case conditions, the Caithness area could experience voltage collapse, where the preventing action would be a fast run-back or run-up of the CM HVDC link depending on the transmission direction. This is the Emergency Power Control function (EPC).

In addition, it was found that the normal converter control characteristics needed to be changed during extremely weak AC network conditions. The signal to trigger this change is the System Status Signal North of Beauly (SSSNoB) derived from switchgear status information across the north of Scotland to determine whether a discontinuity at 275kV between Spittal and Beauly has occurred.

Below is a figure showing the load flow simulations for different network configurations and converter dispatches. These kinds of graphs are usually referred to as PV-curves. It can be seen in the curves that for some network configurations, at a power level far below the power rating of the CM HVDC link (800MW), the voltage drop is significant for just a small increase of dispatched active power from the HVDC link therefore risking a voltage collapse and it is not possible to transmit full power on the HVDC link.

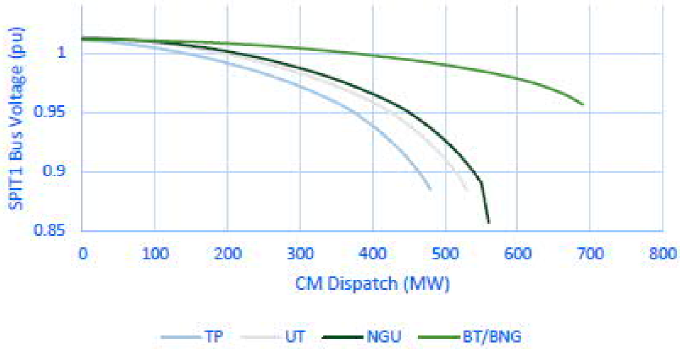


Figure 5. PV analysis exploring different outages and converter dispatches.

Dynamic studies were done to establish the required timing and ramp rate for power run-back/run-up to prevent voltage collapse. The following figure is showing simulation plots for a case, Case 01, where a voltage collapse takes place, and the corresponding case 01a where a successful emergency action from the CM HVDC link has taken place.

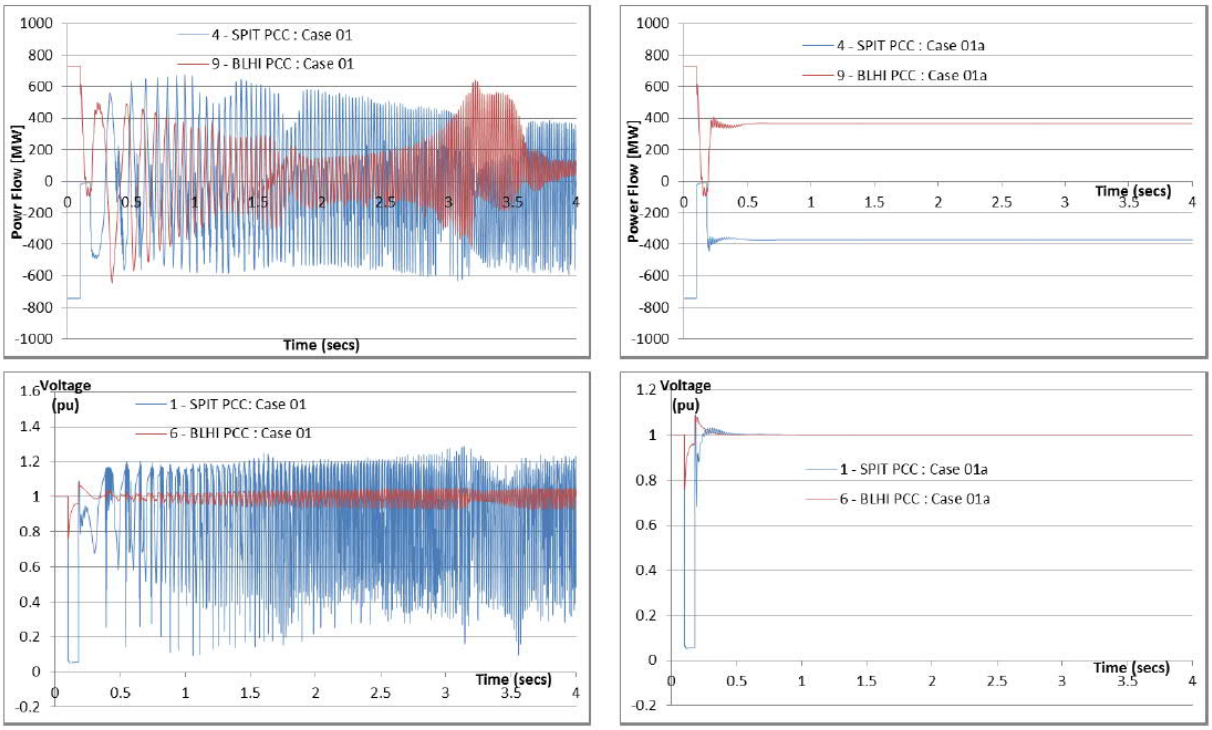


Figure 6. The two left-hand graphs showing a voltage collapse without EPC, and the right-hand graphs showing a successful run-back.

3. IMPLEMENTATION OF THE CM HVDC LINK ANCILLARY SERVICES

Based on the planning studies and the design studies for the CM HVDC link, it was decided to implement a slower function correcting marginal overload on the circuits PM1 and PM2 preventing thermal overloads of the 132kV conductors. This function, the Automatic Power Order Limiter (APOL), continuously monitors the PM1 and PM2 circuits and automatically changes the dispatch on the CM HVDC link decreasing the power transfer on those circuits to a loading within their rating. The ramp rate used for this function is approximately 200MW/min.

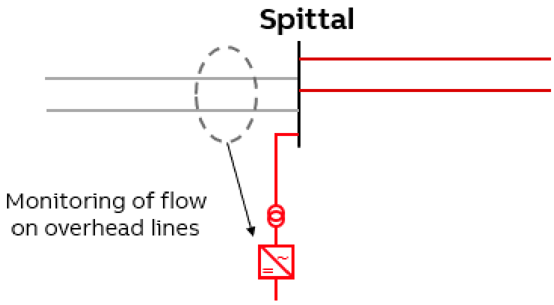


Figure 7. The HVDC control system in the CM HVDC link monitors the power flow on the 132kV circuits PM1 and PM2 and acts with APOL or EPC.

For higher overloads where a voltage collapse is imminent, a fast-acting control, Emergency Power Control (EPC), was implemented. Based on the monitored PM1 and PM2 circuits, it acts with a pre-set ramp rate of approximately 2000MW/s, responding within 30ms.

To detect the incident for which the AC network fault level could drop very low and for which condition the converter control needed to switch to a power control characteristic suitable for an extremely weak AC network, a bespoke network monitoring scheme called SSSNoB (System Status Signals North of Beauly) was designed and implemented by SHE Transmission. The SSSNoB scheme monitors the status of switchgear on the 275kV network between Spittal and Beauly Substations which it uses as inputs. The output status signal from SSSNoB goes high if there is a complete loss of 275 kV connection between Beauly and Spittal busbars (for example, a double circuit outage somewhere along the 275kV transmission corridor). This output signal from SSSNoB triggers the HVDC control system to do a fast transition from the normal power control mode to extremely weak AC network control mode. It is latched and so return to normal mode is by operator action.

4. THE CAITHNESS-MORAY-SHETLAND HVDC Link

4.1 Design and engineering for a five terminal HVDC system

To be ready for future HVDC extensions, the Caithness Moray HVDC link is designed and tested as a five terminal HVDC system. The first stage is point-to-point Caithness-Moray (Commissioned December 2018), the second stage would see a third HVDC terminal on the Shetland Isles linking into a DC switching station close to Noss Head in Caithness (subject to windfarm development on Shetland and regulatory approvals), and the third stage is for further expansions.

The following figure gives an overview of the current point-to-point transmission system between Spittal and Blackhillock converter stations, together with the foreseen multiterminal HVDC system expansion with the Kergord converter station and two future converter stations, A and B.

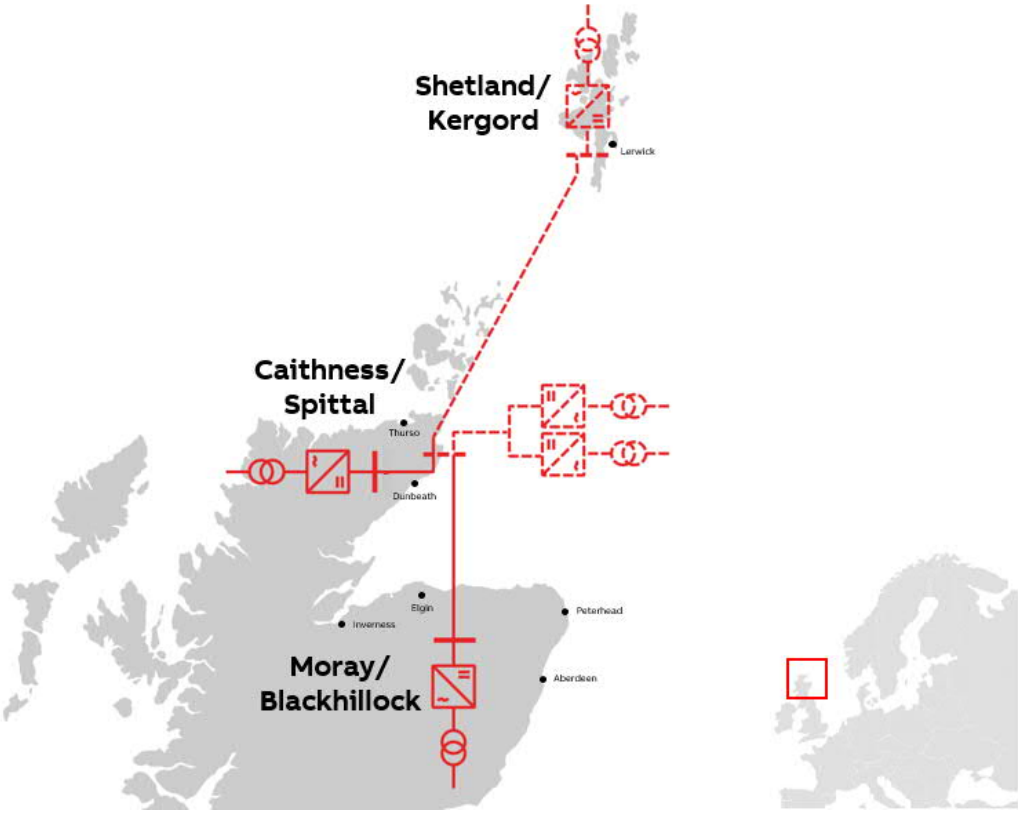


Figure 8. Caithness Moray HVDC Link in northern Scotland is designed for a five terminal HVDC system (straight lines). The foreseen extension is shown with dashed lines, where the DC switching station is at the midpoint for the multiterminal system shown as a dashed busbar.

For the system design, the five terminals in the HVDC multiterminal VSC system have been assumed to have the following parameters:

Symmetrical monopole system, +/-320kV$_{DC}$

Blackhillock in Moray	1200MW
Spittal in Caithness	800MW
Kergord on Shetland	600MW
Future A/Future B offshore	800MW each

DC choppers with breaking resistors were assumed to exist in all stations except for the Blackhillock converter station. DC choppers with breaking resistors are used to control the DC voltage during faults in the AC network connected to an inverter by consuming excess power and thereby keeping the DC voltage within tolerance. This method enables the DC power transmission to be resumed upon isolation of the fault, and hence the DC chopper together with its breaking resistors is available for successful fault ride-through required for the frequency control of the connected AC networks.

The requirements for the DC switching station, at the midpoint of the multiterminal system, were to be able to connect four DC cable circuits and to energise cables with limited disturbance of the DC system during power transmission. Therefore, the DC switching station will be equipped with high-speed by-pass switches and pre-insertion resistors, where the resistor is limiting the cable in-rush current in the beginning of the energisation, and thereby decreasing the DC voltage dip disturbance on the rest of the DC system. When the DC cable voltage has increased sufficiently, a high-speed switch by-passes the resistor to prepare for power transmission.

Spittal converter station, Blackhillock converter station, Kergord converter station and the DC switching station were designed in detail during the project, while Future A and Future B converter stations are planned to be designed at a later stage.

To properly dimension the three DC cable circuits, the three converter stations and the DC switching station, extensive rating studies were undertaken. Special considerations were made for the multiterminal system, taking into account the different modes of operation for the five terminal HVDC system. For the energisation study and especially the energisation of several cables at the same time both the AC and the DC side were studied and rated. During the short circuit current study, the summation of the short circuit currents from all the five HVDC converter stations feeding into the fault were taken into account [3]. In the over-voltage studies the energy contribution from all the five HVDC converter stations were considered. Multiterminal fault ride-through studies were undertaken to rate for the energies through the two DC choppers and breaking resistors.

To assure harmonic performance, energisation performance, fault ride-through performance, black-start performance and dynamic performance, multiterminal studies were conducted with the complexity of different modes of operation for the multiterminal HVDC system. During the performance studies, EMT (Electro-Magnetic Transient program) simulation software was used, where the AC network, the five converter stations and the DC network were modelled in detail and where the virtual control and protection system, VMACH2, were used for all five converter stations. VMACH2 is the same software as used in the control and protecti0n system to be delivered but considers the latencies as introduced by the hardware in the real system, and thereby facilitates the verification of the performance already in the study phase instead of later during the Factory System Test (FST). Additionally, a more complex AC network model can be used during the study phase, including detailed models of wind farms, compared to what is feasible during the FST where a real time simulator is the simulation platform. Hence, to capture performance issues and find remedies early in the project the use of VMACH2 reduces the risk for the overall project.

Besides the control and protection system for the Spittal and Blackhillock converter stations, the control and protection systems for the Kergord converter station and the DC switching station, both hardware and software, were designed and manufactured.

4.2 The DC Grid master controller

To coordinate all the signal exchanges needed between the different converter stations during start-up and shut-down, a DC grid master controller was designed, constructed, tested and commissioned. This DC grid master controller is used today for the point-to-point transmission between Spittal and Blackhillock and is ready to be used for the future multiterminal transmission when it is built and commissioned. The DC grid master controller manages all the interlocks between Blackhillock, Spittal and Kergord converter stations and the DC switching station, including DC grid sequences, but will not handle those for the Future A and Future B converter stations.

4.3 The factory system testing of a five terminal HVDC system

The purpose of the factory system test is to test the functionality of the control and protection, both software and hardware, on the system parts that have not yet been tested in the project. Since the control performance verifications had already been done early in the project through simulations with EMT simulation software together with VMACH2, only testing of protection is needed together with testing of the AC switchyard controllers, DC switchyard controllers, DC Grid master controller, communication and the Human Machine Interface (HMI).

To test the functionalities, a real-time simulator was used, where all three converter stations, Spittal, Blackhillock and Kergord and their associated DC cable systems were modelled in detail. The AC system, the wind farms and the two converter stations Future A and Future B, only needed to be included as simplified models, since the control performance already had been verified in the previous dynamic performance study phase. As mentioned previously, this early verification is important to reduce the risk in a point-to-point HVDC project, but it is essential for a multiterminal project considering the many modes of operation. The simplified model for all the wind farms on the mainland was a single current injection source with similar fault recovery behaviour as a real wind farm, and for Future A and Future B converter stations the same approach was used.

Specifically, for the multiterminal system during the FST, all the signal exchanges were tested between the three converter stations and the DC switching station handled by the DC grid Master controller.

4.4 Replica of the Control and Protection System

Replicas were constructed and tested for the control and protection systems of Spittal, Blackhillock and Kergord converter stations and the DC switching station, to facilitate the possibility of future multiterminal FST of Future A and Future B control and protection systems. Also, a copy of the DC grid master controller was included. This replica system was commissioned in The National HVDC Centre in Cumbernauld, Glasgow in Scotland.

SHE Transmission values the use of replicas for additional real-time assurance of the control performance of the Caithness-Moray-Shetland HVDC scheme in multiple potential scenarios.

5. CONCLUSION

HVDC links with subsea cable systems are a viable option for building longer power transfer corridors within the same synchronised network. They can avoid planning risk associated with onshore overhead lines and can provide valuable system support such as voltage stability and black-start capability. Several such projects are in the planning process today and the Caithness-Moray HVDC link commissioned during 2018, which crosses the Moray Firth in the North of Scotland, is an example of this application, where the benefits of early delivery for connection of renewables to limit carbon emissions supported by favourable cost benefit analysis made it the preferred solution compared to onshore AC transmission rebuild options.

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