The National HVDC Centre

Part of Scottish & Southern Electricity Networks

Maximising HVDC Support for GB Black Start and System Restoration

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Executive Summary

"Black Start" refers to the re-energisation of the electricity grid following a system shutdown. It relies on designated power-stations with a self-starting capability to start energising a section of the network, then incrementally connecting loads and additional generators to create 'islands' of energised network, and then connecting these 'islands' together to re-establish a stable grid network.

The electricity grid in Great Britain (GB) is one of the most stable in the world, and total or partial shutdowns are rare and unlikely events. However, the partial system outage on 9th August 2019 shows that unexpected events can happen; and it is the responsibility of all electricity network licensees, Black Start contracted generators, the System operator and to a degree, non-Black Start generators (who are obliged to obey emergency instructions unless there is danger to life or equipment) to plan for such events, and ensure that the network is restored quickly and safely.

The changing profile of generation in GB has the potential to make the effect of severe network disturbances more impactful in the future. This occurs with the reduction of thermal generation on the Network (with their associated large rotating machines) potentially resulting in, without other intervention, a declining strength and stability of the Network (i.e. system inertia and short circuit level). These effects not only may give rise to challenges for the containment of voltages and frequency excursions of the system, but also make the worst-case scenario of re-energising the network more difficult following the event. (This being since the restoring system is less stable in its early stages as additional loads and generation are connected to it, and new sources of power may require minimum levels of system strength before contributing to restoration).

High Voltage Direct Current (HVDC) transmission technology offers a potential solution to this. HVDC interconnectors connect the GB grid to the electricity grids and markets of other countries, hence they can access independent power supply for re-starting parts of the Network following a complete shutdown. HVDC links within the GB system (e.g. Embedded links and offshore wind farm connections) can also contribute to later stages of system restoration.

Increased capacity from HVDC interconnectors up to 26GW[1] are proposed to connect to the GB network over the coming years to 2030. HVDC interconnectors based on voltage source converter technology have the potential to provide excellent Black Start capabilities (as well as other areas of system support able to increase system stability and reduce the impact of network disturbances). HVDC projects are individually large in scale- larger than single conventional generation units on the existing network that provide black start and are set to be more broadly distributed in connection across the GB system than they have been in the past. Therefore, there is an opportunity for HVDC interconnectors to not only support Black start, but also together with suitable Embedded HVDC links on the onshore GB transmission system (an example being the recently commissioned Caithness-Moray VSC-HVDC project) "leapfrog" areas of more problematic network restoration, energising large geographic areas more rapidly to provide a faster and more flexible approach to restoring demand.

However, to achieve this, and maximise the benefit of these future HVDC schemes, we have concluded from our analysis that changes in our approach to Black Start are required. With costs of providing Black Start services forecast to potentially increase by a factor of 10 over the next 10 years compared to prices in 2014[2], the Scottish

[1] National Grid Electricity System Operator- "Interconnector Register", 03 October 2019
[2] National Grid (2014), Benefits of Interconnectors to GB Transmission System.

Government requested that the National HVDC Centre to investigate how to maximise the opportunity that the use of HVDC schemes to support Black Start energisation presents, primarily from a technical perspective.

The National HVDC Centre, commissioned by the Scottish Government, has methodically and objectively reviewed how HVDC schemes can be utilised to support Black Start energisation from a technical perspective (i.e. the commercial and regulatory processes have not been considered, but areas such as technical frameworks and codes have). Based on this review, eight key recommendations have been proposed and discussed with GB Transmission Network Owners and Operators at a consultation workshop held on 17 September 2019:

1) **Define early specification of HVDC Black Start controls and functional requirements for new projects.** We understand that there would be challenges for HVDC manufacturers and developers to re-engineer Black Start functionality at later stages of project development, whereas allowing future HVDC schemes to specify Black Start functionality at an early stage (for example ensuring black start controls are included in the design) would not necessarily increase costs over those incurred in normal design. Therefore, it would be appropriate for BS control functionality to be a standardised requirement on all future HVDC schemes. The decision to demonstrate the BS capability would continue to be taken at a later stage and would be informed by the National Grid ESO Black Start contract and procurement strategy at that point, with potentially a wide range of cost efficient options available to it than would otherwise have been the case.

2) **Develop extensive and robust whole-system testing and verification processes for network protection systems during Black Start.** Black Start is a highly unusual situation, and we are likely to have very little operational experience of the response of AC transmission network protection (or the HVDC system protection) to faults under the very weak conditions associated with a newly formed power system. It is therefore recommended that the protection settings for both the AC transmission system and HVDC system are extensively tested (as a combined system), for restoration scenarios, including protection systems on distribution networks. We note that the National Grid ESO is currently engaged in work to understand further the options for black start from distribution sources and we believe these recommendations may complement that work.

3) **Carry out detailed Black Start analytical studies of HVDC control systems in Black Start conditions.** The capability of HVDC links to provide Black Start energization and restoration is limited by the converter ratings and control considerations. Hence, significant studies and data exchanges to support them across the industry are required. A further consideration at the later stages of restoration are operational processes and bespoke control strategies to ensure the HVDC link controls transition as expected from Black Start mode to normal operation without tripping. This consideration is most critical when re-energised networks re-synchronise with each other- each potentially having been supported by HVDC.

4) **Develop a detailed commissioning requirement for Black Start provision from HVDC interconnectors that goes beyond Factory Acceptance Testing and includes standardised system testing with real-time simulations and field acceptance testing.** Currently any HVDC Black Start functionality is tested at the factory and this does not give the required level of confidence that it would act as expected on the real network. Therefore, combining factory testing with real-time demonstration and field trials would build confidence in the robustness of the solutions.

5) **Develop a vision for Black Start provision in HVDC-rich areas identifying the role that other devices such as synchronous condensers need to play.** The Black Start services that HVDC schemes provide could be significantly enhanced if combined with other technologies such as synchronous compensators which can increase system strength on a weak power island and provide fault currents for reliable operation of the protection systems in weak grids. Therefore, the role of synchronous compensation devices and other complementary technologies should be considered for future HVDC schemes.

6) **Ensure that Black Start criteria do not form a barrier to entry forms of technology and service provision.** The System Operator (SO) commissions Black Start services from a range of provider, but there are a number of criteria that need to be met to qualify; some of these criteria are not appropriate for HVDC schemes and therefore should be reviewed to ensure that we do not unnecessarily dis-qualify HVDC schemes who could provide valuable Black Start and system restoration services.

7) **Create an integrated training program for control room personnel and operators to implement HVDC-led Black Start.** In principle, electricity control room operators need to communicate with network (Transmission and Distribution) owners and Black Start service providers to restore power to customers. However, inadequate or complex information can increase the risk of incorrect operation across system restoration. Therefore, continuous training of personnel on operation of grids with high levels of HVDC links and other low-carbon technologies, combined with simple, clear and effective communication approaches among all stakeholders is required to ensure reliable system restoration.

8) **Other areas of investigation.** We note that whilst the recommendations above are HVDC focussed as per the centres remit, in principle a number of these above points could have broader application to a range of convertor based technologies- for example Batteries, Solar PV and Wind turbines There are additional possible HVDC Black Start enhancements that merit further investigation; offshore windfarms (or island generation) to help energise the network, and potentially reducing system voltage during restoration to speed-up the time to restore the system.

This study has investigated HVDC state-of-the-art technologies, Black Start processes, existing codes and obligations, as well as international experience. Our report concludes that there are key high-level opportunities that could be explored to maximise the use of HVDC for Black Start and system restoration in GB. We have also considered the specific opportunities of HVDC in the context of existing Black Start technical requirements and existing Black start strategies, focussing in particular to the Black Start restoration options available to the Scotland and North of England area from HVDC technologies.

Case Study of Black Start in Northern Britain

The current GB Black Start strategy is based on six different zones, with Northern Britain comprising three zones formed by Scotland, North East England and North West England. Scotland and North of England are potentially the most vulnerable zones in terms of having a low system strength under normal operation due to the high concentration of renewables. However, the three zones have three existing HVDC schemes (Moyle, Western Link, and Caithness-Moray) and could host up to four additional HVDC schemes by 2027. The future HVDC schemes include two key cross-border interconnections (North Sea Link (NSL) and NorthConnect, between GB mainland and Norway), two embedded schemes (Eastern Link) and two Island connections (Shetland and Western Isles). Such

HVDC transmission infrastructure with enhanced control capability and flexibility can in principle provide more than sufficient Black Start and other ancillary services options required for system restoration and reliable operation. A summary of the key findings of the case study are:

- The planned cross-border HVDC interconnectors (NSL and NorthConnect), which are based on voltage source converter (VSC) technology can inherently provide Black Start and system restoration services to GB using the power sourced from hydro resources in Norway, in the event of a total shutdown. This capability to energise network and load is more than equivalent to that from conventional resources previously available.
- Also, embedded VSC-HVDC links with both terminals in GB (Caithness-Moray and the future Eastern HVDC links) could provide support during later stages of system restoration to speed up load restoration between remote load and resources within Scotland.
- Future Island HVDC connections (Shetland and Western Isles) have potential contribute to re-energization and restoration of the main grid, but further development is required to demonstrate the self-start capability and self-regulation of voltage and frequency control at the remote wind farms on these islands.
- HVDC links based on the classic line-commutated converter (LCC) technology (Moyle and Western Link) would require additional compensation equipment; hence they are less likely to contribute to system restoration services compared to VSC-HVDC schemes. However, the potential performance of LCC schemes across Black Start and system restoration should be kept under review should synchronous compensation of sufficient scale be taken forward to complement Black start and other factors of system stability.

This report concludes that the Scottish Government should engage with the developers of planned HVDC schemes (notably the two Norway-connected links NSL and North Connect) to support appropriate arrangements for provision of Black Start and system restoration services are designed, implemented and tested on these future HVDC links, subject to further review by NGESO, Office of Gas and Electricity Markets (Ofgem) and The Department for Business Energy and Industrial Strategy (BEIS).

Also, the electricity system operator and transmission owners should support the development and demonstration of Black Start specifications for future embedded schemes (Eastern HVDC Links), Island connections (Shetland and Western Isles) and HVDC-connected wind farms, where appropriate to complement speed and effectiveness of restoration.

It is our view that these recommendations will help to improve GB's Black Start capability (and reduce system restoration time) by maximising the future benefit from HVDC schemes. The rationale for these recommendations is described in the full report and outlined below:

- First, GB Black Start arrangements is described in the context of the changing generation mix (Section 1);
- Next, an overview of existing and upcoming GB HVDC schemes is illustrated (in Section 2);
- Analysis of HVDC capability across BS technical requirements using RAG status is presented (in Section 3);
- Key findings are discussed with focus on a case study Scotland and North of England zones (in Section 4);
- Then, global HVDC BS experiences and recent international black outs are outlined (in Sections 5 & 6); and
- Recommendations and next steps are highlighted in Section 7.

Abbreviations

Abbreviation	Meaning
BESS	Battery Energy Storage System
BS	Black Start
BSS	Black Start Strategy
BSSP	Black Start Service Provider
CCGT	Combined Cycle Gas Turbine
DER	Distributed Energy Resource
DNO	Distribution Network Operator
DSO	Distribution System Operator
EC	European Commission
ESO	Electricity System Operator
EU	European Union
EWIC	East West Interconnector
FFR	Fast Frequency Response
GB	Great Britain
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
LJRP	Local Joint Restoration Plan
LCC	Line-Commutated Converter
LJRPs	Local Joint Restoration Plans
NETS	National Electricity Transmission System
NIA	Network Innovation Allowance
NG	National Grid
NGESO	National Grid Electricity System Operator
OWF	Offshore Wind Farm
OWSD	Offshore Wind Sector Deal
NSL	North Sea Link
PLL	Phase-Locked-Loop
RoCoF	Rate of Change of Frequency
SCL	Short Circuit Level
SCR	Short Circuit Ratio
SO	System Operator
TRL	Technology Readiness Level
TSO	Transmission System Operators
UPS	Uninterrupted Power Supply
VSC	Voltage Source Converter
VSM0H	Virtual Synchronous Machine – Zero Inertia

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1 Introduction

Electricity generation, supply and use is changing rapidly in Great Britain (GB). In the unlikely event of a total or partial shutdown of the electricity transmission network, System Operators (SO) use Black Start (BS) services to re-energise the grid and restore power to consumers as quickly as possible. However, over the last decade, the changing nature of generation mix within GB grid has led to rising operational challenges and costs of current conventional Black Start providers. Also, the closure of large thermal power stations with self-starting capability to be potentially replaced by more distributed sources of generation has focussed attention on GB Black Start and system restoration arrangements. Over this period, National Grid ESO has explored innovation projects and new service tenders to expand the range of options for provision of Black Start services.

Black Start restoration forms an important part of security of supply. Traditionally it has been provided by large synchronous power stations, particularly coal. The electricity industry and government have identified this as a substantial challenge to our security of supply and are now supporting initiatives to find new sources of Black Start provision. Following an increase in Black Start costs in 2015 [1], National Grid ESO has been required to publish an annual Black Start Strategy and Procurement Methodology. The 2019 Black Start statement [2] acknowledges that need for change and lays out a vision which includes a fully competitive Black Start procurement process involving a wide range of technologies.

High Voltage Direct Current (HVDC) interconnection between Britain and its European neighbours represents one source for future Black Start provision. HVDC technology is not a source of generation in itself; rather it is an alternative to High Voltage Alternating Current (HVAC) technology used for the implementation of circuit connections in electricity transmission systems. HVDC systems can also facilitate the integration of more renewable generation, enable electricity interconnection between the grids of different countries and deliver system support services required for reliable operation of the wider power system. Whilst HVDC links between GB and the electricity grids of other countries will not primarily be built to provide Black Start services, where such interconnection technology is capable, there is an opportunity for enhancing Black Start and resilience provision for GB and Scotland.

HVDC converters can be configured to provide the key functionality of Black Start services, due to their enhanced voltage and frequency control capability. However, HVDC schemes may not perfectly replicate all the BS services which can be delivered by conventional synchronous generation, and the potential implementation of such HVDC-derived BS services have not been fully explored yet in GB. Detailed analysis and other key technical considerations associated with HVDC BS service are discussed within this report, which in turn inform the specifications and processes by which the contribution of existing and future HVDC schemes to Black Start can then be managed. The Scottish Government engaged The National HVDC Centre to investigate the potential of HVDC schemes to support the provision of electricity system Black Start and power restoration services in GB. In response, this report will focus on:

- Overview of key drivers for change in the GB electricity mix and the development of HVDC schemes;
- Outlining the capability of GB HVDC schemes to provide Black Start and system restoration services;
- Highlighting opportunities for improving the security of electricity supply using HVDC schemes; and
- Identifying key enablers and considerations for HVDC technical performance across Black Start.

1.1 Drivers for Change in GB Electricity System

The three key drivers for change in the GB electricity network as identified in [3] are decarbonisation, decentralisation and digitisation. Both the UK and Scottish Governments have published energy strategies for achieving for a future energy system that is smart, sustainable and affordable [4][5]. The GB electricity system needs to develop in an economic, efficient and coordinated way to meet decarbonisation targets, boost security of supply and deliver optimum benefits to energy consumers [6].

1.1.1 Emissions Reduction Directives

Over the past few years the generation mix connected to the British electricity system has changed significantly, a process that is expected to continue (See Table 1). These changes include substantial reduction in the capacity of coal power station from 25GW to 10.2GW between 2012 and 2018, and the increase in non-synchronous renewable generation capacity from 12.2GW to 42.8GW, across the same period. In Scotland, electricity supply in 2012 included two large coal stations at Cockenzie and Longannet, both of which are now closed. The result of these changes to the generation portfolio has been a substantial reduction in carbon emissions assorted with electricity generation. For example, the carbon intensity of electricity generation in Scotland has dropped from 255gCO_2 / kWh in 2012 to just 54gCO_2 / kWh in 2016 [7]. By 2025 it is expected that no coal-fired station will be operational in GB following the UK Government's decision to ban coal generation from that year [8], whilst according to National Grid's 2019 Future Energy Scenarios the total capacity of wind and solar generation could be between 42GW and 61GW.

Table 1: Electricity generation Capacity in Great Britain [9]

	2012	2018	FES Range for 2025
Total generation capacity	94.4GW	107.4GW	116GW - 132GW
Of Which Coal	25.0GW	10.2GW	0GW
Of Which Wind	7.6GW	21.0GW	28GW - 41GW
Of Which Solar	0.4GW	12.7GW	13.9GW – 20.4GW
Synchronous Generation	82.2GW	65.1GW	45GW - 58GW
Non-synchronous generation	12.2GW	42.8GW	60GW - 84GW

1.1.2 Renewable Energy and Net Zero Targets

In May 2019, the Committee on Climate Change recommended that the UK should aim to achieve net-zero greenhouse gas emissions by 2050, and that Scotland should do so by 2045 [10][11]. Achieving these targets will require fast and deep decarbonisation across the energy system. It will mean continuing decarbonisation of electricity supply as well as an increased role for the electricity system in supplying energy to transport and heat sectors.

At UK level the growth of renewable generation was kick-started by the commitment to meet 15% of energy from renewable sources in 2020 [12]. In Scotland, there has been a more direct target based on renewable electricity aiming to generate the equivalent of 100% of Scottish electricity consumption from renewables in 2020 [13], which had resulted in renewable electricity equivalent to 75% of electricity demand being generated in 2018 [13]. This trend is likely to continue as the focus moves towards targets for 2030 and net zero commitments are likely to mean for electricity generation, and the potential need to bring new energy demand onto the electricity system in the form of Electric Vehicles and Heat Pumps.

At a UK level there are no renewable energy or electricity targets beyond 2020, however the UK Government has signed up to the carbon reduction target laid out in the 5th Carbon budget of achieving a 57% reduction on carbon emissions compared with 2019 [14]. The Scottish and Welsh governments have set explicit renewable energy targets for 2030, aiming to supply 70% of electricity demand from renewables in Wales [15] and a target of 50% of total energy consumption from renewable sources in Scotland [16].

Achieving a low or zero carbon electricity system does not just mean replacing the generation of electrical energy from renewable sources, but also replacing the services that large-scale synchronous generation has traditionally provided. The Scottish Government identified this in its Networks Vision in 2019 [17], highlighting the need to consider a secure and resilient electricity transmission network, and has highlighted the importance of identifying how the technical services that the system needs can be supplied from renewable sources to ensure 'sustainable security of supply'.

1.1.3 EU Electricity Interconnection Targets

Electricity markets in GB and the rest of Europe are physically linked by subsea cables, known as interconnectors. The 2015 EU Energy Union package highlighted the need for increased levels of interconnections in order to better facilitate a single European energy market, with a minimum target of interconnection in each country to reach 10% of generation capacity by 2020 [18], with a further increase to 15% expected by 2030 [19][20].

The existing and proposed interconnectors in GB are based on HVDC transmission technology. At present, GB has 5GW of installed interconnection capacity. GB currently imports more electricity than it exports to the rest of Europe [21]. Net imports in 2018 were equivalent to 8% of the GB electricity demand, and this is expected to increase in future as several interconnector projects are under development [22].

The UK government supports the development of at least 9GW of additional HVDC interconnection capacity as a part of its strategy to decarbonise the energy mix. Increased cross-border interconnection with Europe's electricity systems will boost the security of electricity supply in GB, support grid integration of more renewable technologies and facilitate better energy trading and balancing.

1.2 Consequences of Changes in GB Electricity System

The closure of large thermal power stations and increased penetration of distributed low-carbon generation technologies and interconnections has focussed attention on the GB electricity system strength. Key operational parameters that provide important services for reliable system operation such as system inertia, short circuit level and Black Start capacity of generators will be impacted as discussed as follows.

1.2.1 Declining Black Start Generation Capacity

Black Start Capability is contracted from 'an array of strategically located' thermal, hydro and pumped storage stations, which can re-energise the electricity system [23]. In 2015, coal-fired power stations were among the predominant Black Start providers in the UK. However, coal-fired stations will have a limited role in future Black Start services in GB, with many coal generation units already either closed or scheduled for decommission [24].

The current Black Start and system restoration method in GB is based on a bottom-up approach (self-start up BS units without external power supply) to deal with total and partial system black out events. As the electricity system strength reduces and the number of BS providers decline, the system restoration strategy must be adjusted. Otherwise, re-starting the power system becomes dependent on a very small proportion of generation remote from the load, thus resulting in weaker power islands which are prone to larger voltage deviations and would require additional reactive power support locally [23].

National Grid reported that Black Start costs are forecast to increase by up to a factor of 10 over the next 10 years compared to prices in 2014. HVDC interconnectors and links could potentially decrease GB Black Start costs by assessing generators in areas which are not blacked out, assuming the remote end converter station is not disconnected [23][25]. The HVDC schemes can also potentially enable quicker restoration for the transmission system and provide access to a greater diversity of fuel sources, thereby improving overall resilience.

1.2.2 System Inertia Reduction

System inertia is a measure of the resilience of a power system to certain types of disturbances (such as a sudden loss of generation or demand). The spinning mass in the electricity grid— generally mechanical turbines’ and synchronous generators’ shafts at the production end of the network and motor rotors on the demand side — creates the system’s inertia. Conventional power generation possesses inertia. System operators use inertia services to assist their grids to absorb sudden changes of power loading/generation [26]. As conventional synchronous generation-based power plants are retired, the increase of non-synchronous low-carbon technologies such as wind, solar generation sources and battery energy storage that are connected through power electronic converters will provide less inertia, leading to reduced GB system strength [27].

Inertia reduction can potentially increase the risk of frequency instability of the power system. During a power mismatch between demand and generation, the system frequency deviates from its original value. A power system with low inertia will inherently experience a higher rate of change of frequency (RoCoF) than a power system with large inertia, and will require additional control actions to contain the frequency deviation within operation limits. For a loss of generation on the power system, if the RoCoF exceeds the setting of RoCoF-based loss of mains protection relays on distribution networks, then additional distributed generators will be disconnected from the network, thus resulting in a further drop of frequency on the system.

1.2.3 Short Circuit Level Reduction

Short circuit level (SCL) is a measure of how extensive a disturbance is, and how quickly the system recovers following a disturbance [28]. Transmission system SCL currently dominated by synchronous generators is declining, and this will potentially increase the risk of instability on the power system.

National Grid ESO Stability Pathfinder project is currently investigating how devices and equipment which contribute to system short circuit level can support the resilience of network protection, phase locked loop (PLL)-based converters, retained voltage levels and voltage angle change and withstand [28]. Such plant, if made available under normal system conditions, would be expected to be consistent with existing generation to complement where possible Black start restoration.

Short circuit level reduction could potentially impact the following aspects of system operability:

- Network protection – Electricity transmission (and distribution) protection systems are designed and configured to meet a certain level of SCL. For low SCLs, the performance of protection systems will need to be re-assessed to ensure reliable operation.
- Stability of Phase Locked Loop (PLL)-based converters - Inverter based technologies such as HVDC links and wind farms use PLL devices configured to track AC transmission system phase angle reference assuming quality performance at a certain level of SCL. For low SCL, PLL-based technologies could be at risk of losing the system phase angle reference, thus resulting in unstable performance.
- Retained voltage levels – During a disturbance or fault, the measured voltage across the network is referred to as the retained voltage. Areas with high SCL have a higher fast fault current injection which means higher retained voltages within the transmission and distribution systems away from the fault compared to areas with low SCL. If the retained voltages drop below specifications in Grid Code, generation is at risk of tripping.
- Voltage angle change and withstand - Voltage angle of the system is defined by the action of generators to support an acceptable voltage profile across the system to support power flow. During a fault or disturbance, the voltage angle is supported immediately by synchronous generators. For areas with low SCL, the voltage angle deviation will be larger and more rapid during a disturbance compared to high SCL areas. In low SCL conditions, PLL-based devices will be at risk of losing system phase angle reference due to a volatile voltage angle movement, which could result in generation trip or unstable operation.

1.2.4 Black Start Grid Code Requirements

According to the European Regulation on electricity emergency and restoration, transmission system operators (TSO) connected through interconnectors are required to provide Black Start support to a requesting TSO in emergency state, provided this does not cause the responding TSO to enter emergency or black out state [29].

If the system restoration service is to be provided through HVDC interconnectors, then it is assumed that the remote end HVDC converter station is not disconnected. The Black Start and system restoration support will consider the HVDC support capability and may consist of the following actions [29]:

- Manual regulation of the transmitted active power to help the TSO in emergency state to bring power flows within operational security limits or frequency of neighbouring synchronous area within system frequency limits for alert state defined pursuant to Article 18 (2) of Regulation (EU) 2017/1485;
- Automatic control functions of the transmitted active power based on the signals and criteria set out in Article 13 of Regulation (EU) 2016/1447;
- Automatic frequency control pursuant to Articles 15 to 18 of Regulation (EU) 2016/1447 in case of islanded operation;
- Voltage and reactive power control pursuant to Article 24 of Regulation (EU) 2016/1447; and
- Any other appropriate action.

1.3 Components of GB Black Start Services

In general, Black Start services involve a complex and gradual process starting from the self-start of a power generating unit, supplying in-house (auxiliary) loads of the generation station, re-energising key transformers and transmission lines, providing energised paths for non-Black Start units, picking up loads according to their criticality, and resynchronisation between energised networks. GB Black Start processes are geographically based and formalised via Local Joint Restoration Plans (LJRPs) implemented by Black Start service providers (BSSPs), transmission system operators (TSOs) and distribution network/system operators (DNOs or DSOs).

The process of system restoration is then carried out by Transmission Owners (TOs), DNOs and the ESO. Local Joint Restoration Plans represent pre-agreed processes by which the local TO and DNO are able to instruct a Black Start station and then use the resources provided by that station to begin building a power island. In the middle and later stages of a restoration NGESO takes operational control as individual power islands are then synchronized.

Power stations which do not have a Black Start contract do not have an obligation to be technically available before or during a restoration, however if they are technically available and it is safe to do so they are obliged under sections OC9.4 and OC9.5 of the GB Grid Code to respond to emergency signals from the ESO [30].

Current BS services of the GB system are mainly provided by large transmission-connected generators, and the ESO electricity system restoration plan (as highlighted in [31]) is based on two key aspects: commercial contracts with BSSP, and a 'restoration strategy' agreed and tested by key BSSPs, DNOs and the ESO to deliver the following:

1.3.1 Self-start up Capability without External Electrical Power

Self-start capability refers to the ability of the BSSPs to start up their generation unit(s) from a complete shutdown stage to an operating stage condition without an external power supply. This will require the Black Start generation unit to be equipped with a standby power supply source (e.g. rotary generator or an Uninterrupted Power Supply (UPS) battery) with enough capacity to supply in-house and auxiliary loads of the generation station/unit. The self-starting generation unit needs to have both voltage and frequency control capabilities required for supporting islanded AC network operation during the system Black Start procedures.

1.3.2 Re-energising Part of GB Transmission Network Capability

NG ESO currently uses a top-down approach for re-energising the GB National Electricity Transmission System (NETS), which involves creation of a 'Skeleton Network' to extend the auxiliary supplies provided by Black Start providers to non-Black Start providers, and re-energising a part of the electricity distribution system. During this stage of Black Start system restoration, the generation units considered as parts of the energised Skeleton Network should be capable of overcoming any technical and operational challenges related to charging currents and switching on of transformers, transmission lines, and distribution networks (e.g. magnetic inrush currents and transient over-voltages). Also, they should be capable of managing voltage through a substantial reactive power range and frequency.

1.3.3 Block Loading

Block (pick-up) loading following a complete or partial black out is normally a gradual process with flexible limits of operating voltage and frequency during island modes. During this stage, the frequency operational limits are relaxed (within the range of 47.5Hz and 52Hz) when compared to normal operation to align with the ESO BS technical requirements. For instance, at transmission voltages above 145kV AC transformers are typically specified to withstand over-fluxing of no more than 20s at 47Hz and a maximum of 15minutes at 49.5Hz. In practice, control engineers could operate the network between 49.75Hz and 51Hz and attempt to regulate the frequency to 50Hz across block loading. To achieve successful block loading, BSSP generation unit needs to be capable of accepting instantaneous loading between 30-50MW, without tripping or causing instability issues on the energised power islands [31].

During this phase other restoration service providers with no Black Start facilities could contribute to increasing the power generation capacity and operational capability of the energised Skeleton Network to pick up more loads, hence improving the system restoration process. These could include other non-Black Start generation units, renewable generation sources, and HVDC interconnectors as examples.

1.4 Overview of HVDC Schemes

This section describes the technical benefits, capabilities and limitations of HVDC technology.

1.4.1 Technical Benefits

Over long distances, HVDC technology is more efficient, has lower electrical power losses and better control capabilities compared to HVAC technology. In addition, HVDC can interconnect power systems operating at different frequencies and phase angles. This is not possible with HVAC technology. Therefore, HVDC is the appropriate technology for electrical links with Scandinavia, mainland Europe, and the island of Ireland from Great Britain (GB) for long subsea cables known as Interconnectors.

At subsea transmission distances typically beyond 100-120 kilometres and at a voltage of 220 kV and above, HVAC technology is not practical due to the large capacitance and hence charging current of the subsea cables. HVDC systems also have a lower environmental impact because they require fewer overhead lines or underground cables to deliver the same amount of power as HVAC systems.

1.4.2 Comparison of HVDC Technologies

The two main HVDC converter technologies are line-commutated converter (LCC) and self-commutated voltage source converter (VSC). LCC is a mature technology, suitable for bulk power transfers and typically requires reactive power compensation up to 60% of the active power transmitted and switchable harmonic filters. VSC technology is a more recent development, which has independent control of active and reactive power, improved Black Start capability and reduced filtering requirements than LCC technology. LCC technology is mainly based on power electronic thyristors, which is a semiconductor device that can be turned on and off by control action but relies on the AC line voltage to achieve commutation from one switching device to another. VSC technology uses Insulated Gate Bi-polar Transistors (IGBTs) switches which can be turned on and off by control action without regard for the state of the AC system [32].

During normal operation, VSC-based HVDC schemes are synchronised with the AC voltages and system frequency of the surrounding AC grids through their associated phase-locked loops (PLLs). Under black out events (assuming one converter terminal is still energised), the blacked-out VSC PLL will no longer provide such synchronisation, and the converter needs to provide locally the reference voltage and frequency required for the power island operation.

This grid-forming operation requires a specific mode of control which functions purely for Black Start conditions and will not be applicable when the voltage and frequency of the power island become subject to more than one source of dominant control [32]. However, LCC-based HVDC schemes must have a relatively strong AC voltage at both ends of local and remote converter stations for reliable operation, hence Black Start arrangements with LCC would require additional equipment such as synchronous condensers to support local converter station during system restoration [32][33].

It is easier to reverse power flows and hence form multi-terminal HVDC grids with VSCs than LCCs. A reversal of power flow direction in VSCs is achieved by a change in the direction of current with a fixed polarity of the DC voltage, compared with LCCs which require a change of the voltage polarity.

1.4.3 Limitations of HVDC Schemes

LCC technology is available on commercial terms at HVDC transmission voltages of up to 1100kV and rated power of 10GW via overhead lines, while VSC technology is available at DC voltages up to 400kV in service with 525kV under construction and rated power of up to 1.4GW. However, for subsea HVDC transmission, the maximum power transfers achieved with LCC technology is limited is 2.2GW at a DC voltage of 600kV, due to the transfer capabilities of available HVDC cable technologies [32].

VSC technology is compatible with both paper-insulated mass-impregnated non-draining (MIND) and plastic-insulated cross-linked polyethylene extruded (XLPE) HVDC cables, whereas LCC schemes typically use paper-insulated HVDC cables, which are typically more expensive than the plastic-insulated cables used for underground or subsea electricity transmission [32]. LCC technology occupies (approximately 60%) more space than an equivalent VSC station, due to the requirement for reactive compensation and harmonic filter banks [32]. A typical filter bank connected to a 400kV AC system is 30m by 30m [32]. VSC stations require larger building footprints than LCC stations, but much less outdoor switchyard and filter areas. The transmission losses per converter station are about 0.7% of transmitted power in LCC technology and up to 1% of transmitted power with VSC technology. LCC technology requires special AC voltage transformers, but VSC technology can use conventional transformers depending on the converter topology [32].

In addition, LCC technology is a line commutating converter, which requires a strong external reference voltage to support its operation from the system. Therefore, for LCC to contribute to a Black Start service, it must be complemented by other technologies such as synchronous compensators with enough capacity to establish a strong enough AC voltage for the converter to commutate. Beyond this, LCC can also be subject to under-voltage blocking following a disturbance (e.g. due to short circuit faults or large inrush current), and this could potentially impose limitation on its fault-ride-through capability.

2 HVDC Applications in GB

HVDC links are evolving in the GB grid, where the total installed capacity of HVDC schemes doubled from 4000MW in 2017 to 8000MW in 2019. This section describes the existing and future HVDC schemes.

2.1 Architecture of GB HVDC schemes

In 2017, there were only 4 HVDC electricity interconnections, comprising 2000MW to France (through the interconnector known as IFA), 1000MW to the Netherlands (BritNed), and two interconnectors of 500MW each to the Irish grid (known as Moyle and East West Interconnector (EWIC)). At present, there are 7 HVDC links, including the 1000MW Nemo interconnector to Belgium and two embedded HVDC schemes known as Western Link and Caithness-Moray. By 2027, there are plans to deploy up to 21 HVDC links connected to the GB grid. Table 2 is a summary of the existing HVDC schemes in GB.

Table 2: Summary of Installed HVDC Schemes in GB [34] - [41]

Country	Project Name	Topology	Maximum Capacity (MW)	DC Voltage (kV)	Converter Technology	Completion Date
FR – GB	IFA2000	Interconnection	2000	±270	LCC	1986
GB – NI	Moyle	Interconnection	500	±250	LCC	2002
GB – NL	BritNed	Interconnection	1000	±450	LCC	2010
GB – IR	EWIC	Interconnection	500	±200	VSC	2013
GB	Western Link	Embedded	2200	±600	LCC	2017
GB	Caithness-Moray	Embedded	1200	±320	VSC	2018
BL – GB	NEMO	Interconnection	1000	±400	VSC	2019
Total Capacity (MW)			8,400			
BE-Belgium; FR-France; GB-Great Britain; IR-Ireland; NI- Northern Ireland; and NL- The Netherlands						

2.1.1 Electricity Interconnections

Electricity interconnectors use HVDC subsea cables to connect the GB grid to neighbouring countries for energy trading and balancing. Interconnectors derive their revenues from congestion revenues, which depend on the existence of price differentials between electricity markets at either ends of the interconnector. European regulation governs how interconnection capacity is allocated via market auctions. Figure 1 shows the schematic diagram of a point-to-point HVDC interconnector, which connects two adjacent electricity grids.

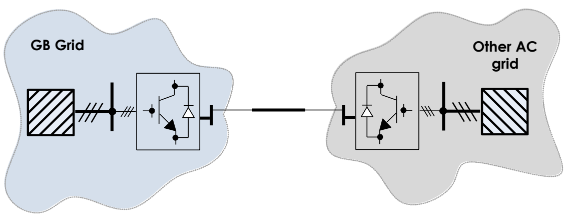

Figure 1: Schematic diagram of a point-to-point HVDC Electricity Interconnector

Interconnectors tend to be privately owned on a commercial basis with two types of investment arrangements either based on a regulated cap-and-floor mechanism or developers seeking exemptions from regulatory requirements and certain aspects of European legislation in order to increase safeguards for their investment.

2.1.2 Embedded Links

Embedded HVDC links use two onshore converter stations remotely located from each other and connected to the same electricity grid for transmission reinforcement, boundary capability improvement and integration of renewable power generation. Embedded HVDC links are implemented in parallel with existing HVAC transmission circuit. They typically tend to be owned by a single or multiple Transmission Owners as a part of their regulated asset base, depending on the network owners of the connection terminals. Figure 2 shows the schematic diagram of an embedded HVDC link example.

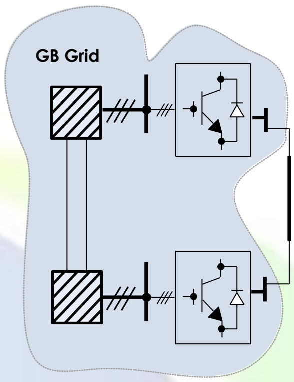

Figure 2: Schematic diagram of a point-to-point HVDC Electricity Interconnector

2.1.3 Offshore Wind Connections

HVDC-connected offshore wind farms can facilitate long distance subsea power transmission connections to remote offshore wind farms. The key components are offshore platform for hosting the offshore converter station, subsea HVDC cables and onshore converter station. At present HVDC-connected offshore wind farms are consented but have yet to be built in GB. Electricity connections to GB offshore windfarms are typically built by offshore wind farm developers through a regulated competitive process and then transferred to an offshore transmission owner (OFTO) under the OFTO regime. Figure 3 shows the schematic diagram of a HVDC-connected offshore wind farms.

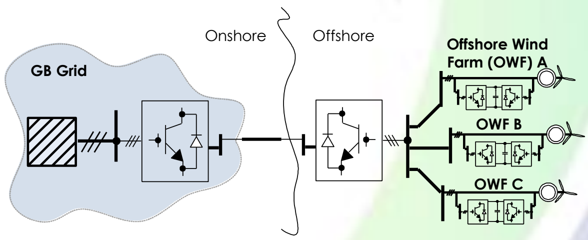

Figure 3: Schematic diagram of an HVDC-connected offshore wind farm

2.1.4 AC Island Connections

HVDC links can be used for the implementation of electricity transmission circuits to remote islands through either extension of an existing HVDC scheme or an embedded HVDC scheme. GB onshore transmission owners typically build transmission infrastructure linking remote islands to the mainland.

Alternatives regimes such as competitively appointed transmission owner (CATO) mechanisms and other emerging regulatory models are being developed for introducing competition in the delivery of GB's onshore electricity networks. Figure 4 shows the schematic diagram of an HVDC-connected AC island (e.g. Shetland) with a DC bussing point to form a three-terminal HDC link.

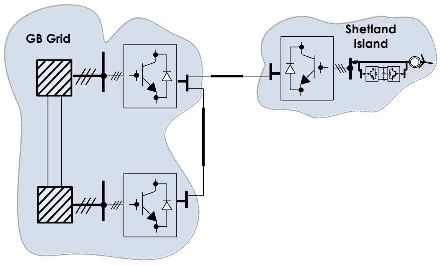

Figure 4: Schematic diagram of HVDC-connected Island into a multi-terminal HVDC scheme

Figure 5 shows the schematic diagram of an embedded HVDC-connected AC island system (e.g. Western Isles Island) with a parallel HVAC transmission circuit.

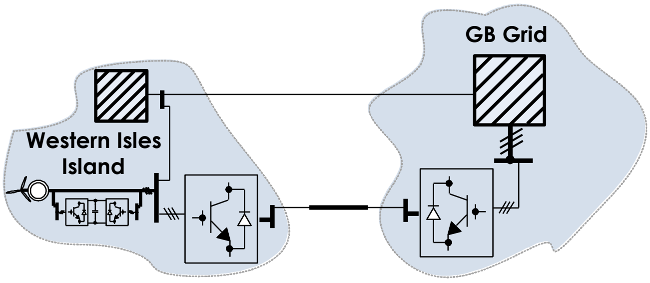

Figure 5: Schematic diagram of HVDC-connected AC Island with parallel HVAC transmission circuit

2.2 Potential Contribution of HVDC Schemes to System Restoration

In GB electricity system, contracted BSSPs need to have Black Start generation unit(s) with self-start capability (i.e. constant standby power supply available on the site and not to rely on external power sources). This in addition to the capability of energising local transmission networks, and block loading (increase load rapidly in blocks, e.g. between 30 MW and 50 MW at a time) [31].

At present, technical specifications and commercial arrangements of the ESO system restoration plan do not, necessarily, support the HVDC schemes (e.g. interconnectors) to be considered as one of the key BSSPs in the GB system. This is because HVDC converters are not Black Start generators in the same way that ESO BS Strategy defines [42], although, the HVDC interconnectors provide access to cross-border power supplies independent from the GB grid with diversity of generation types and capacities (e.g. Europe countries). This can potentially enable the HVDC interconnectors converter stations on the GB mainland to provide the functionality of conventional Black Start generation units (e.g. acting as virtual synchronous generators with active and reactive power control) if appropriate converter technologies and control strategies are implemented [43].

The GB HVDC embedded schemes can also be considered as an important infrastructure to complement existing Black Start arrangements and potential HVDC interconnectors Black Start capability to provide several operational services (due to their enhanced controls) required by TOs and the ESO to support the GB system restoration strategy.

The technical capabilities of different HVDC schemes for providing Black Start services are evaluated in more detail in section 3. Whilst this section presents a high-level discussion on the potential of HVDC schemes to support the existing GB ESO system restoration plan actions (pre-agreed in LJRPs) as follows [31].

2.2.1 Review and Instruct Stage

During this stage, the ESO assesses the status of the system, establishes the appropriate approach for restoration, and contacts BSSPs, TOs and DNOs to instruct them accordingly. The HVDC converter stations considered as contracted BSSPs (i.e. interconnector) or non-contracted BSSPs (i.e. embedded or non-contracted interconnector) can both form part of this assessment and restoration approach.

The HVDC converter stations treated as contracted providers (with access to external power supplies, see HVDC CS1-3 in Figure 6 as examples) will provide Black Start services, starting from energising the substations where they are connected to, and enabling the growth of newly formed power islands and wider system restoration. This of course will require the implementation of the appropriate technical, communication, and commercial arrangements between the GB ESO and the TSOs on the cross-border regions.

The non-contracted HVDC BSSPs (shown as HVDC CS4 and CS5 in Figure 6) will not provide Black Start services. However, they can still play an important role for enhancing reactive and active power control, and providing fast frequency response during the later stages of system restoration.

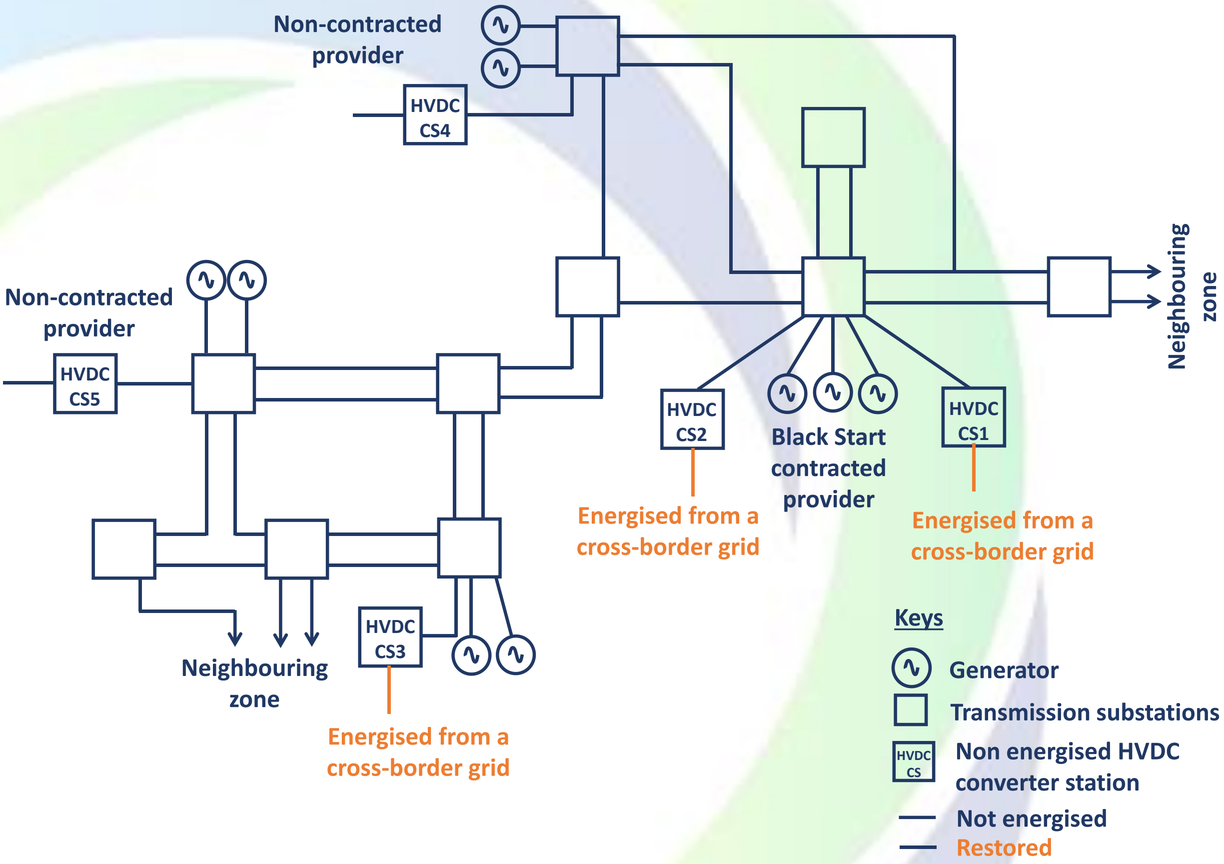

Figure 6: Modified layout of a review and instruct step 1 of the GB ESO BS restoration plan including HVDC [31]

2.2.2 Start-up Stage

The ESO system restoration plan requires the contracted BSSPs must be able to start up their generation units without any external power supply from the dead network, and must also energise their local network and supply the local demand during the start-up stage. In the case of HVDC links, remote power supply is always required to energise the associated DC link, and power the local converter station to provide supply for local networks and demands. However, it can be argued that although the HVDC converter stations normally rely on power supply from remote ends, there are many cases where these remote ends are not part of the blacked-out network even during complete national black out (e.g. cross-border GB-EU HVDC interconnectors). Figure 7 shows CS2 as an example of a converter station initially energised from a cross-border grid and acted as a contracted BSSP.

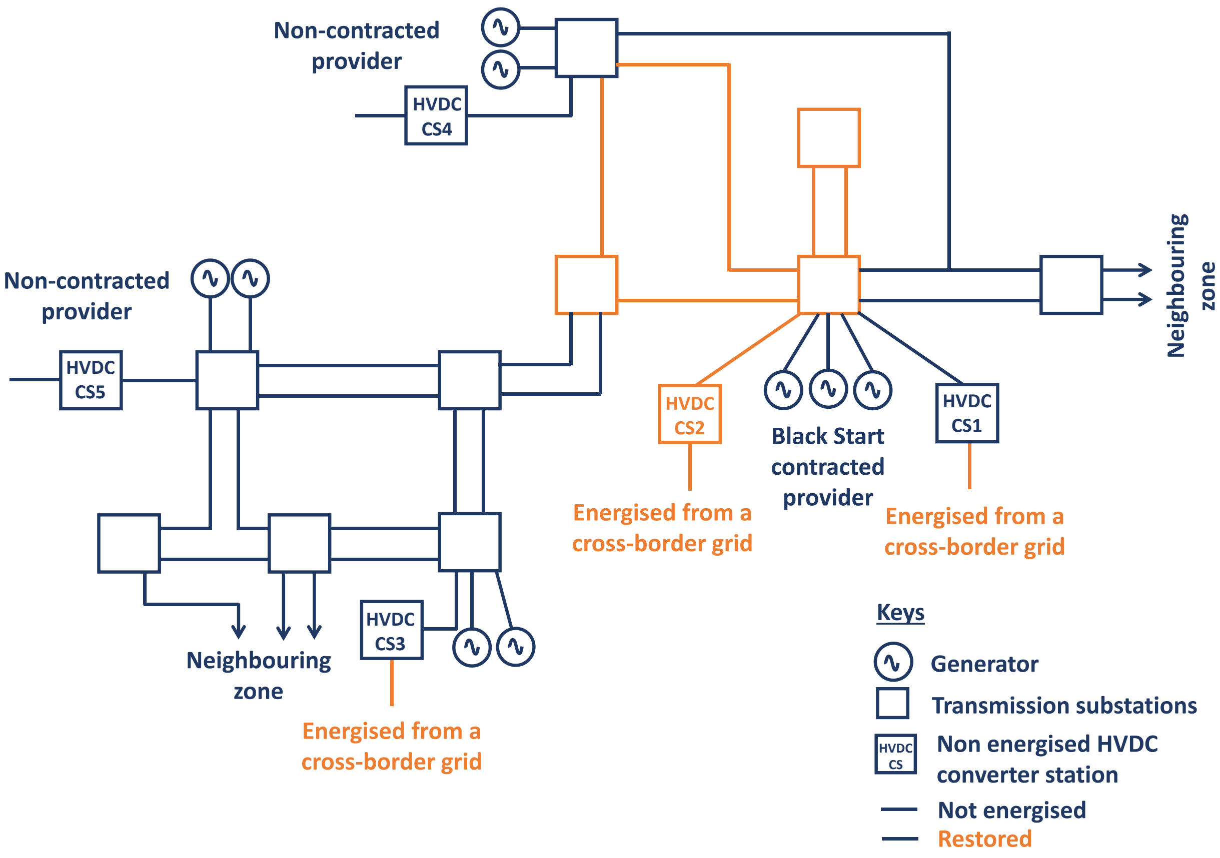

Figure 7: Modified layout of a start-up step 2 of the GB ESO BS restoration plan including HVDC [31]

2.2.3 Power Islands Stage

During this stage, the BSSP is required to 'carefully match their output to the amount of demand in their area'. This is meant to be carried out by each individual demand groups with a BSSP and local network operating as a power island and not connected to other islanded networks or to the wider network. Having HVDC converter stations as a part of this procedure, can significantly improve the stability of the newly formed islands by providing more and rapidly controlled reactive and active power. For example CS1-CS3 (see Figure 8) when they become a part of the formed islanded network, more access to other strong grids will be available. Consequently, more AC transmission lines can be energised and more loads can be picked up, leading to faster restoration time in comparison to conventional Black Start approaches.

2.2.4 Skeletal Network Stage

At this stage, the system restoration is still limited and the power islands are being joined together. More transmission lines will be energised with few non-Black Start generation units. This stage is called by the ESO 'a skeletal network'. HVDC links could be used to facilitate the connection of the power islands to start establishing the skeletal network, energising more transmission networks and adding more generation as shown in Figure 9.

This stage typically features the connection of more customers progressively until full power supply is restored. VSC-based HVDC schemes can achieve a reversal of power without a change in voltage polarity. This can help to manage energy supply and demand on the established skeletal network and facilitate quicker restoration of power supply to associated loads compared to conventional AC transmission.

Therefore, HVDC interconnectors can make an important contribution to support all aforementioned Black Start stages, and the HVDC embedded links can potentially contribute to enforcing the skeletal network stage   if they are considered in the future by the ESO in their system restoration plan. Figure 9 shows a schematic layout of a system restoration plan with different HVDC schemes.

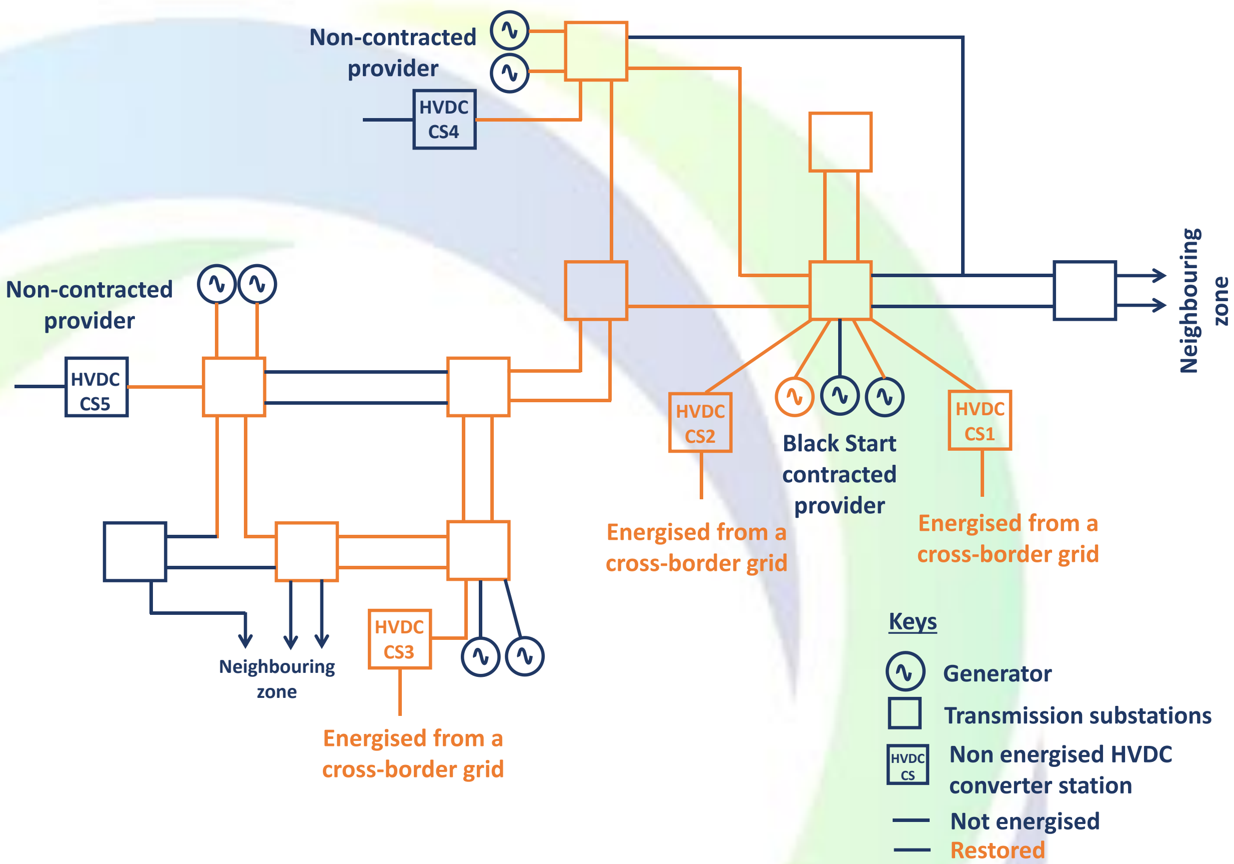

Figure 8: Modified layout of a power island step 3 of the GB ESO BS restoration plan including HVDC [31]

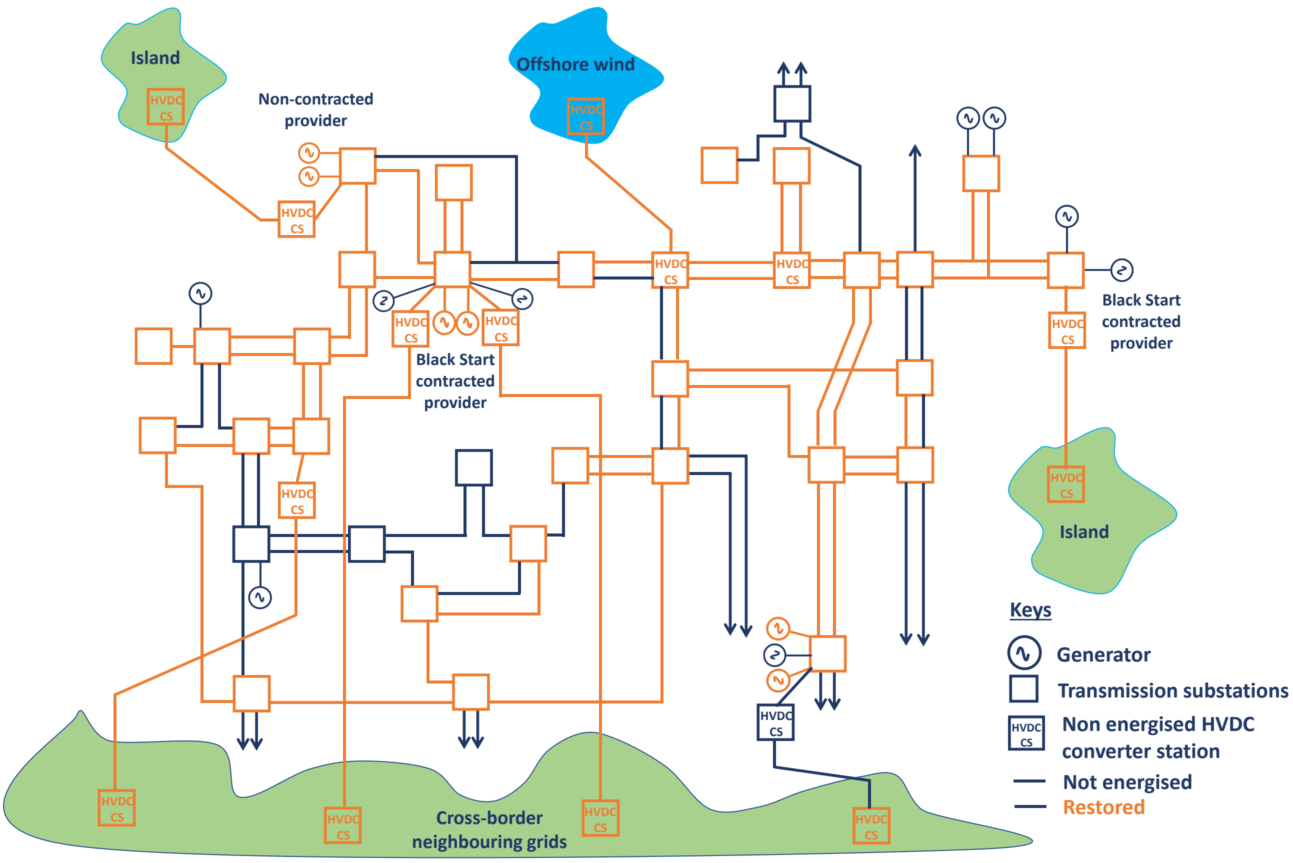

Figure 9: Modified layout of a skeletal network step 4 and 5 of the GB ESO BS restoration plan with HVDC [31]

3 System Restoration Requirements with HVDC Capability

3.1 Technical Requirements for Black Start Service Providers

The GB National Grid ESO has outlined a number of key Black Start technical requirements that need to be met by each potential BSSP. These requirements are detailed in [44] and summarised as follows.

3.1.1 Time to Connect

Following the instruction received from the ESO, the BSSPs should be able to start-up their associated BS plant(s) from shutdown to full operation and energise a part of the GB network within two hours and without the use of external power supplies to comply with the GB Grid Code BS requirements (OC9.4.5.1). BS Grid Code OC9.4.5.1 requirement is defined as "*Certain Power Stations ("Black Start Stations") are registered, pursuant to the Bilateral Agreement with a user, as having an ability for at least one of its gen-sets to start-up from Shutdown and to energise a part of the total system, or be synchronised to the system, upon instruction from the company within two hours, without an external electrical power supply ("Black Start Capability")* [45].

3.1.2 Service Availability

The potential BSSP is responsible for demonstrating BS service availability at least 90% of each year. High BS services availability (≥90%) is required for the ESO to use them in the instance of a Black Start 'which could happen at any time'.

3.1.3 Voltage Control

The BSSP needs to have the ability to control AC voltage level during the Black Start sequences (network energisation, expansion and block loading) within acceptable steady state operational limits (±10%).

3.1.4 Frequency Control

The BSSP needs to have the ability to control frequency during the Black Start sequences (creating and expanding islanded networks and block loading) within the range of 47.5Hz to 52Hz.

3.1.5 Resilience of Supply BS Service

Under this requirement, the BSSP must be able to provide BS services for a minimum duration of 10 hours.

3.1.6 Resilience of Supply BS Auxiliary Unit(s)

The BSSP should be able to continuously run their associated auxiliary units for a minimum of 3 days.

3.1.7 Block Loading Size

The BSSP should be capable of accepting instantaneous loading of demand blocks of at least 20MW. The 20MW power capacity is assumed to be manageable for DNOs to switch their loads, and sized to provide a start-up supply for a conventional non-Black Start station.

3.1.8 Reactive Power Capability

It is required for the BSSP to be able to re-energise parts of the GB transmission system with no loads (MVAr>0, MW=0), hence providing the reactive power required for charging currents absorbed or injected by electricity system equipment. The BSSP needs to have reactive power capability ≥ 100MVAr (leading) for energising transmission lines, and achieving a quick access to other non-Black Start units and demand.

3.1.9 Sequential Start-ups

To allow managing contingencies such as possible tripping of BS units or transmission or distribution networks during system restoration, the BSSP must have the ability to perform at least three sequential start-ups across the black start operation.

Potential BSSP must be able to provide all of the aforementioned technical requirements by themselves, or by contracting with other parties if all of the above cannot be met by the Black Start provider. If a potential BSSP has a limitation on one of the technical requirements, the ESO allows Expressions of Interest (EoI) to be submitted, and where possible assesses whether the BSSP not meeting all of the requirements can still participate.

3.2 System Requirements versus HVDC Capability

3.2.1 Analysis using RAG status

This section analyses and compares the technical capability of different HVDC applications versus the GB Black Start technical requirements during a total black out and a partial black out condition. Table 3 is a summary of the HVDC technical capability during a total black out. In Table 3, a colour code is used to indicate the GB HVDC schemes readiness for BS services. Green indicates inherent capability of the associated scheme, amber highlights the changes that are required for enabling the scheme to provide BS services, and red shows the limitation of the schemes for providing BS services.

Table 3: HVDC schemes technical capability against total black out on the GB mainland grid

Category		**Interconnections (with energised DC link)**		**Embedded Links**		**Offshore Wind Links**	**Islands Network interfaced to the GB mainland**	
ESO BS Technical Requirements		**VSC**	**LCC**	**VSC**	**LCC**	**VSC**	**Interfaced by a VSC-based multi-terminal HVDC link to the GB main land**	**Interfaced by a hybrid HVAC VSC-HVDC**
		A	**B**	**C**	**D**	**E**	**F**	**G**
1	**Time for the converter to start-up and energise part of the network (≤ 2hrs)**	Self-commutated and can create an AC voltage [43].	Complementary technologies e.g. synch. compensation or equivalent are required to create a sufficient voltage & SCR to allow effective commutation [33] plus meeting the requirements B3-B9	During a complete blackout event, embedded HVDC links will be part of the dead network. Thus, they cannot provide Black Start services. However, they do have the capability to support the system restoration later stages as a part of the transmission system.		Limited by wind availability and requires synchronisation to an established AC terminal for self-start & back-energisation of HVDC link.	Existing local generation should be sufficient tp back-energise HVDC link. With future wind generation, E1 is applicable.	Similar to F1
2	**Service Availability ≥90% of Each Year of the Service**	above 96% [46]	above 95%			Offshore 90%, and onshore up to 95% [48][49]	Similar to E2	Similar to E2
3	**Voltage Control Capability (within ±10%)**	Inherent voltage control capability is available [47].	Requires synchronous compensators to establish an AC voltage with sufficient SCR to ensure commutation is not lost [33]. Ability to withstand inrush currents & transient voltages during network energisation.			Maintaining stiff AC voltage for energising the offshore inter-array cables, offshore converter and HVDC circuit to enable adequate voltage control at onshore AC network is a technical challenge [50].	Similar to E3	Similar to E3
4	**Frequency Control Capability**	Frequency control is available for 0MW to rated power if the transition from active power control to frequency control mode is implemented [43][47].	Requires synchronous compensators with enough inertia to slow RoCoF that the LCC can track and ramp up its power accordingly.			Requires power curtailing control for minimum production & fluctuating power due to wind speed variations. VSC needs to change from grid-following to grid-forming control mode, and BESS may be required for FFR.	Similar to E4	Similar to E4
5	**Supply BS Service >10hrs**	Applicable [47]	Applicable when B3, B4, B7 and B8 are met.			Requires 1-5% of its rated capacity power supply to energise yaw & pitch mechanisms for self-start plus HVDC converter auxiliary units [50].	Similar to E5	Similar to E5
6	**Supply Auxiliary Units >72hrs**	On-board backup supply normally installed	Similar to A6			Similar to A6	Similar to A6	Similar to A6
7	**Block Loading Size (≥20MW)**	Inherent fast active power response and control capability [43][47]	Sufficient reactive power is required to avoid commutation failure, and enable power import [33].			If E3 and E4 control requirements are met, aggregation of wind farms may deliver power up to 5 days [51].	Similar to E2	Similar to E2
8	**Reactive Power Capability (≥100 MVAr leading)**	Independent reactive power control capability	Requires synchronous compensators and enough reactive power capacity to support the LCC commutation and system energisation [33].			Similar to A8(if requirement for back-energization of offshore converter and the HVDC circuit is met)	Similar to E8	Similar to E8
9	**Sequential Start-up (≥3 attempts)**	Multiple self-start up capability on dead and weak AC grids [43].	Possible when B3, B4 and B8 are met.			Possible with a strong AC voltage is established at the terminal & 1-5% of its rated capacity power supply to energise yaw & pitch mechanisms for self-start and emergency braking [50].	Similar to E9	Similar to E9
TRL*	**GB system environment**	**6** (Pilot scale technology demonstration [24])	4 (Technology development with system validation in a laboratory environment)			**3** (Research to prove feasibility and experimental proof of concept)	**3** (Similar to GB system TRL in E)	**3** (Similar to GB system TRL in E)
TRL*	**International experience**	**9** (System operation over full range of conditions [24][43][47])	7 (System commissioning at full scale demonstration [33])			**5** (Technology development with laboratory scale system validation in a relevant environment)	**Not applicable**	**Not applicable**

***Technology readiness level (TRL) definition are adapted from [28].**

3.2.2 Key Findings on HVDC Technical Capability across BS and Restoration

The key findings from the above analysis are outlined below for different HVDC topologies. Also, the time sequences (and associated delays) between HVDC Black Start and system restoration phases for all the HVDC schemes should be investigated further to inform operations across emergency restoration.

Interconnectors

- HVDC interconnectors will have access to independent power supply from the GB grid (energised from a cross-border grid), and the interconnectors implemented using VSC technology can inherently meet seven out of the nine ESO Black Start technical requirements listed in Table 3 (i.e. requirements A1-A3, A5, and A7-A9) during total and partial black outs.
- Most HVDC converters are typically equipped with battery-based or rotary UPS units to supply their auxiliary systems (e.g. protection and control to meet the technical requirement number 6 in Table 3).
- The BSSP converter terminal of the VSC-based HVDC interconnector needs to be equipped with a frequency-voltage (AC) island control mode (also called grid-forming control mode) to meet the ESO technical requirement A4 (see Table 3). In addition, devices such as synchronous rotating compensators/stabilisers can also be used with the VSC-HVDC terminals to address inertia and fault level requirements if necessary.
- LCC-based HVDC interconnectors require additional equipment to meet the nine ESO BS technical requirements. The key devices required are reactive power compensation devices (e.g. synchronous compensators) with self-starting capability and enough capacity to establish a relatively strong AC voltage and provide reactive power (up to 60% of the LCC power rating) for safe commutation and a reliable BS and system restoration process. The synchronous compensators should also be sized to the level that provides the required inertia for frequency stability of the formed power island supplied by the LCC HVDC link. The scale of the supplementary devices (e.g. synchronous compensators) to enable LCC Black Start could potentially be significant and proportional to the scale of the LCC station. Therefore, it is less likely that LCC-based HVDC interconnectors would have a significant role as BSSPs compared to VSC-based schemes in GB.

Embedded links

- The HVDC links (with all terminals) embedded within the GB mainland power grid will be part of the blacked-out network following a total shutdown event, hence resulting in a lack of access to an external power supply to energise the associated DC links. Therefore, embedded HVDC links cannot provide Black Start services across a total black out condition. However, embedded HVDC links do have strong technical capability to support the connection of power islands and contribute to wider system restoration at later stages of system restoration as a part of the TOs' transmission networks.

Island Connections

- Provision of BS services to the GB mainland from remote islands connected through VSC-based HVDC links will depend on the available local generation capacity on the islands. If the local generation has sufficient capacity, then back-energisation could be possible from the remote terminal through the HVDC link into the mainland (assuming the capability A1-A9 and E1-E9 in Table 3 are met).

<u>Offshore wind farms Links</u>

- The ability of HVDC-connected offshore wind farms to provide BS services and meet the above mentioned ESO technical requirements is influenced by the following:
    - <u>Wind availability and variability</u> – planning and modelling tools can be used by the BSSP to forecast the wind resource across Black Start and system restoration;
    - <u>Availability and size of auxiliary local generators (e.g. diesel or a UPS) for self-start and emergency braking of the wind turbines</u> – a power supply with a size of 1-5% of its rating is required [50]. There might be requirements for additional auxiliary supplies to energise the wind farm inter-array cables and offshore and onshore HVDC converters; and
    - <u>Control capability of the wind farm and the HVDC link to energise the associated AC transmission, block loading and provide stable power island operation</u> – the wind farm and its associated HVDC converters controls need to be developed to operate in a weak grid. For example, conventional wind farms are normally synchronised to a strong onshore grid with rotating inertia (or an AC island network created by an offshore HVDC converter) using a PLL. To enable offshore wind farms (OWF) BS services, the OWF converters need to be controlled to emulate traditional synchronous machines and operate in grid-forming mode instead of grid-following mode (change from PLL-synchronised to self-synchronised operation). Also, such technical requirements could inform the development of advanced power-balance control approaches such as virtual synchronous machine (VSM) schemes, which can be implemented at the HVDC onshore grid side converter. The HVDC grid-side converter with VSM will provide virtual inertia and damping to the blacked-out AC network part (i.e. reference frequency, phase angle and voltage magnitudes), and OWF side converters can be synchronised to the virtual inertia of the VSM to allow stand alone and grid-connected operation.
- In general, the enabling technologies required for offshore windfarms to provide Black Start services is still under development stage (i.e. Technology Readiness Level is approximately 4).

3.2.3 Gaps and Opportunities

The opportunities for HVDC schemes to provide BS services depends on the scheme type and applications, converter technology and location. The diversity of GB's HVDC interconnectors and embedded HVDC link locations will be a key factor in delivering a wide range of BS and system restoration services.

- Technical feasibility studies will be required on case-by-case basis to understand and quantify the HVDC scheme BS capability versus ESO technical requirements. The following requirements need to be considered for a range of operational conditions (e.g. as part of an island with no or very low inertia, interactions between HVDC control schemes, and interactions between HVDC controls and nearby generators and other active control devices such as FACTS):
    - Control and protection requirements of HVDC BS converter stations and the associated blacked-out AC network during energisation from the HVDC schemes (e.g. transition between grid-following to grid-forming operational modes, active and reactive power requirements in the region, fault level requirements, coordination of DC and AC network protection, etc.);
    - Sub-synchronous interactions with nearby generators may occur during the creation of a skeletal network by the HVDC converters, and further investigation into the HVDC controls for mitigation of unintended interactions will be required; and

    - Control and protection requirements for back energization of HVDC terminals from weak AC grids created by wind farms, other HVDC links/FACTS devices or a skeletal network would require further investigation for embedded HVDC schemes and HVDC-connected wind farms.

- Field testing of HVDC BS capability during commissioning, planned outages or demonstration projects can be used to verify grid re-energisation, block loading and re-synchronisation functionalities.
    - Requirements for integration of HVDC Black Start support into existing LJRP arrangements involving other conventional Black Start providers should be further assessed by industry and stakeholders;
    - Effective communication systems combined with operator training is required to ensure HVDC Black Start operation can be delivered as expected;
    - Inter-TSO coordination and commercial arrangements is considered out of scope for this report, but would require further evaluation by HVDC owners and the interconnected TSOs; and
    - Multi-terminal HVDC links can potentially facilitate improved Black Start and system restoration on the GB grid, if the remote converter terminals are equipped with appropriate controls and devices that can support back energisation from weak grids. However, such multi-terminal DC grid controls have yet to be developed or implemented on the GB network and would need to be explored further.

4 Case Study of HVDC Schemes in North of England and Scotland

The current NG ESO Black Start Procurement strategy is based on six contractual zones as presented in Figure 10 (left-hand side) [31]. In each zone, up to three stations are contracted for providing Black Start services. The current and future GB HVDC schemes, based on their locations and technical capability, have the opportunities to provide Black Start services for different zones. Figure 10 (right-hand side) shows the location of HVDC converter stations which can potentially act as a BSSP in Scotland and North of England zones if the technical requirements in Table 3 are addressed. Within these two zones, controllable HVDC sources of import/export power with approximate capacity 6 GW will be available, considering current and future GB HVDC schemes in these regions.

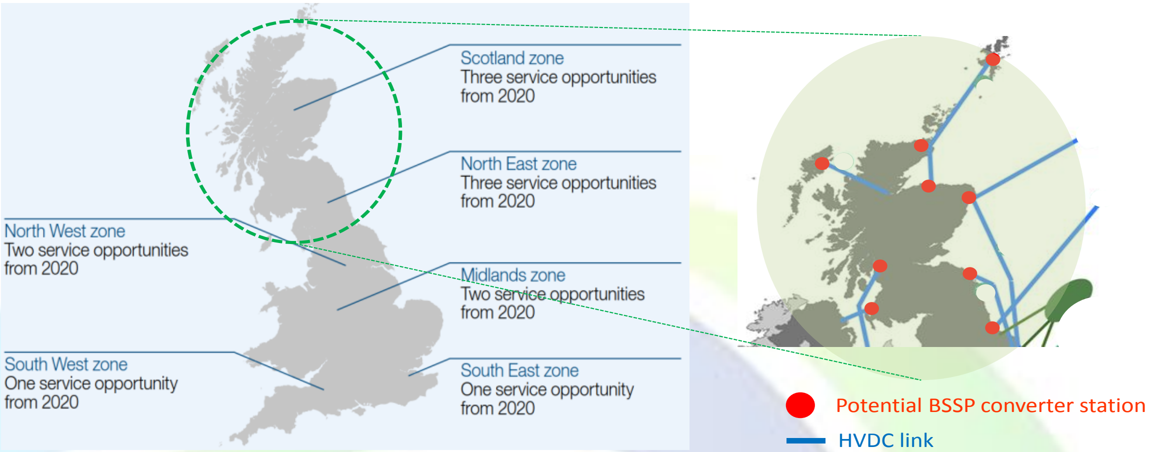

Figure 10: Black Start service opportunities and HVDC potential in Scotland and North East Zone [31].

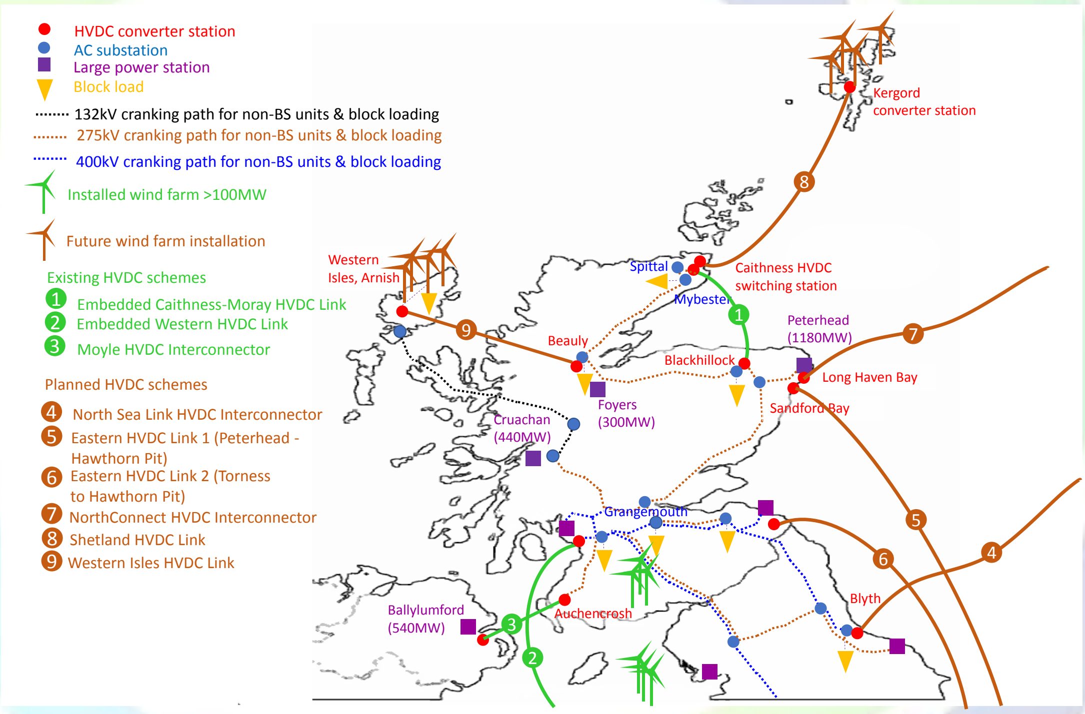

Figure 11: High level layout of HVDC schemes for enabling Black Start and system restoration in Scotland and England North-East/West zones

4.1 HVDC Black Start Services in Scotland Zone – Case Studies

Within the Scotland Zone shown in Figure 11, there are currently four installed converter stations. These represent two VSC terminals of the embedded Caithness-Moray HVDC link, one LCC terminal of the embedded Western HVDC link, and one LCC of the Moyle HVDC interconnector. By 2027, the number of converter stations in Scotland Zone (including Shetland and Western Isles) could increase to 11 terminals.

4.1.1 Existing HVDC Schemes in Scotland Zone

Caithness-Moray VSC-HVDC link

The embedded Caithness-Moray (CM) VSC-HVDC link (shown as link number 1 in Figure 11) is designed to provide BS services to recover from regional black outs at the Caithness area in North Scotland and could potentially provide BS services to the Shetland area.

The capability of CM HVDC link to energise a 275kV AC substation at Spittal in Caithness area has already been successfully tested during the scheme commissioning [52]. However, the test was limited to energising a clean 275kV busbar at the Spittal substation with associated transformers, and neither transmission lines energisation nor block loading functionality was tested. To achieve this, the Blackhillock converter terminal in the Moray area must be energized. Also, the Spittal converter terminal will require operation in island grid-forming control mode with the required frequency response (virtual inertia) for initiating a power island in the region, block loading and enable the growing of the energised islanded network.

The CM link is designed to only provide Black Start services from Blackhillock to Spittal ac network, but not from Spittal to Blackhillock network. However, the Caithness or Moray HVDC terminals could potentially be used for restoring power in Shetland if the proposed future Kergord converter station in Shetland area (see Figure 11) is equipped with the required Black Start technical capability (as outlined in A1-A9 on Table 3).

Then, the Blackhillock via Spittal converter station will charge the HVDC link and the remote converter at the Kergord substation. As shown in Figure 11, the Blackhillock substation is close to Peterhead power generation station (with almost 1180MW capacity). Thus it can potentially be energised via its 275kV AC transmission circuit, following the restoration of Peterhead generation units. The potential interactions between the Blackhillock converter station control with the Peterhead generation unit control across the early stages of system restoration could merit further investigations. This might require Peterhead gas turbine generation units to act as an anchor generator to facilitate the frequency stability and reactive power control.

The system restoration supported by the CM link could include the energisation of the transmission network first by re-energising predefined corridors of 275kV circuits and reconnect more generation in the Zone for example beginning from Foyers pumped hydro station (with 300MW rated capacity and BS capability) and other smaller generators to form a skeletal network with enough generation including the Peterhead Station. Then, the Blackhillock converter station can be re-connected to facilitate restoration of power in the Caithness area via the HVDC circuit connecting to Spittal. Finally, loads and other renewables in the area can be progressively reconnected. This procedure will ensure most of main transmission routes are energised and all charging and transient issues (e.g. over-voltages, inrush currents, etc.) are minimised before the customers are connected.

LCC-HVDC terminals (Western Link and Moyle)

As for the LCC-HVDC terminals in the Scotland Zone (Western Link and Moyle), and with existing infrastructures, there are limited opportunities to make use of these LCC connected terminals to contribute to Black Start restoration processes in the zone. This is because the Western link does not have access to external and independent power supply, and additional synchronous compensation equipment are required to be installed at the Moyle Auchencrosh LCC terminal, as discussed in subsection 3.2. These will include reactive power compensation devices such as synchronous compensators with self-starting capability (e.g. starting motors). The compensators must be able to provide sufficient SCR to establish a strong AC voltage with reactive power capability rated up to 60% of the LCC station power capacity and must be large enough to provide the inertia required for frequency stability of the formed power island supplied by the LCC converters. This seems to be a complex process and may be a costly solution due to the requirements of more spaces, and more equipment to be installed. The Moyle Auchencrosh LCC link will also be challenged by the capability of the North Ireland grid generation capacity to provide the required power for the GB mainland Black Start requirements. Also, the static characteristics on the converter terminals may need to be modified such that the active power control will be at the inverter end (at the Auchencrosh station on GB side) and the DC voltage control will be at the rectifier end on the Northern Ireland side.

4.1.2 Future HVDC Schemes in Scotland Zone

Scotland region will potentially host five more HVDC links with seven converter stations located within the Scotland Black Start zone (see Figure 11). These will include two connections to Shetland and Western Isles, two connections to England (Eastern Link 1 & 2), and one connection to Norway (NorthConnect HVDC Interconnector).

NorthConnect HVDC Interconnector

The NorthConnect HVDC interconnector will be the first electrical link to connect Scotland directly to the European grid (between Long Haven Bay at Peterhead in Scotland and Simadalen in Norway) with capacity of 1.4GW, and through a 650km undersea cable [53]. The interconnector can potentially offer an excellent opportunity to provide Black Start services to the Scotland Zone and GB mainland in the event of a total black out. The following sequences could potentially be considered:

- With appropriate commercial and technical arrangements between the NG ESO and Nordic TSO (Stattnett), the hydropower generation on the Norwegian side can be considered as a remote initial top-down Black Start provider to energise the DC circuit of the NorthConnect link. Then, the Peterhead converter station can be energised to provide a Black Start service to Scotland Zone. The hydropower generation units are normally quick to be turned on and off, and combining this with the HVDC link that has a high-power capacity (1.4GW), the eight ESO Black Start technical requirements indicated as A1-A3 and A5-A9 in Table 3 can be achieved;
- Assuming the Norway terminal is regulating the DC voltage, following a black out event on the GB grid terminal, the Peterhead converter control can transition from a PLL-based grid-following (active power control) mode to a grid-forming mode (islanded operation mode). This will enable the creation of a reference AC voltage with fixed frequency, amplitude and phase angle for Scotland Zone. This will ensure the Black Start technical requirements are met for voltage and frequency control on the newly formed power island (as seen on A4 in Table 3). This is a very challenging control operation, which would require an effective detection strategy for islanding and blackout conditions either using algorithms or switchgear status to switch from PLL-based grid-following mode to islanded mode before the operation of low-frequency demand disconnection schemes (used for load shedding);

- If the converter station on the GB grid-side was regulating DC voltage prior to the black out event, then two control transitions would be required simultaneously to ensure continuous operation of the interconnector following the disturbance. These are: (i) transition to DC voltage control mode from active power control mode at the Norway converter station; and (ii) transition to islanded grid-forming control mode from DC voltage control mode at the GB converter station;
- Then, Long Haven Bay substation transformers at Peterhead can be energised and provide the power supply for starting up the Peterhead generation units. The planned NorthConnect link with a rated capacity of 1.4GW could energise more 275kV circuits in the zone to connect other generators with BS facilities (for example Foyers and Cruachan), or fire up others non-Black Start units, and start re-connecting loads and wind generation in the area; and
- The NorthConnect Peterhead converter station could also provide a remote top-down Black Start service to England Midlands Zone by energising the proposed embedded Eastern HVDC Link 1 (from Peterhead - Drax) (shown as number 5 in Figure 11).

Eastern HVDC Links

Eastern HVDC links are future planned 2 x 2GW HVDC subsea Links between Scotland and centres of demand in England (shown as 5 and 6 in Figure 11, and represents Peterhead – Drax and Torness - Hawthorn Pit link respectively). The Peterhead – Drax HVDC link in combination with the cross-border NorthConnect interconnector form a multi-infeed HVDC infrastructure [54]. Such a multi-infeed HVDC link can potentially provide an excellent Black Start service for restoring the GB system in the event of both a complete black out in the country, or partial black outs in Scotland and Midlands area.

On the Scottish side, the Eastern HVDC Link 1 (Peterhead - Drax) is planned to be located close to the power generation station at Peterhead. The link as shown in Figure 11 will also be very close to the Peterhead converter station of the HVDC NorthConnect interconnector with access to 1.4GW power generation capacity in Norway. This unique location can potentially make the combination of the NorthConnect and Eastern HVDC connections suitable for the provision of Black Start and system restoration services to the GB grid. In the event of a complete black out in GB, the Eastern HVDC link 1 (Peterhead - Drax) can be energised by the NorthConnect converter at Peterhead using energy sources from the Norway grid.

The Eastern HVDC link converter at Peterhead substation would be used in the PLL-based DC voltage control mode, and must be capable of enegizing the HVDC circuit and maintaining stable operation, when connected to AC networks with low system strength (typically below 1 p.u.). One potential way to improve the strength of the AC network at Peterhead is to start-up the Peterhead generation units first, and then energise the Eastern link converter station. If this option becomes unavailable (e.g. due to technical constraints or closure of the station in the future), then additional synchronous compensation devices may be required to improve the system strength at the Peterhead substation, prior `to connection of the Eastern HVDC link. The control of the Eastern link converter at the Drax substation can then be transitioned to a grid-forming mode to provide reference AC voltage with fixed amplitude, frequency and phase angle for the Drax substation to re-energise pre-defined transmission routes and start-up generation in the area.

At the time of writing this report, the converter technology for the Eastern links have not been confirmed yet, and the description of this case is based on VSC technology.

Western Isles and Shetland HVDC links

At present, the Shetland power network is not connected to the GB mainland electricity grid, and the Western Isles has a 132 kV AC transmission connection to the GB grid. With the current situation, there is no spare capacity on the existing Western Isles and Shetland networks to connect additional generation [55]. Scottish Hydro Electric Transmission (SHE Transmission) has recently proposed the construction of a new subsea HVDC link to connect Shetland network to the mainland grid (from Weisdale Voe in Shetland to Noss Head in Caithness), and a new subsea HVDC link to connect the Western Isles network to the GB grid (from Arnish in Western Isles to Dundonnell/Beauly in Scotland). The capacity of each HVDC link is planned to be 600 MW, and the schemes are primarily designed to transfer large amount of power generated by renewables (e.g. wind in Shetland and mix of wind and marine generation in Western Isles) to the mainland grid [55]. In Arnish substation, the following feeders are being connected: (i) Stornaway Grid Supply Point; (ii) Balallan Switching Station (takes feeder from Harris) and (iii) Stornaway Wind Farm. The Scotland Black Start Zone could potentially benefit from the wind generation on these islands and the capability of the 2 x 600 MW HVDC links to provide Black Start services. For example, and as stated in [55] a total of 380 MW of generation is either connected or contracted to connect in the future in Western Isles. The interests from the developers of renewable energy include a mix of onshore wind, pump hydro storage and solar energy projects [55]. Since the generation on the two islands will be mainly wind, it will be relatively challenging to provide a complete set of Black Start services for the Scotland Zone as all the technical requirements listed as F1-F9 and G1-G9 in Table 3 and 4 must be addressed.

The installed power rating of the generation in the islands might be sufficient to meet the no-load losses in the converter stations and HVDC links to energise the associated mainland AC substations (e.g. Caithness and Beauly). However, the capability of the wind farms to manage voltage and frequency on the newly formed islanded power network in Caithness and North West of Scotland would require further investigation.

The potential Black Start services from these islands could be limited to provision of auxiliary supply to the Peterhead power station units. This can be achieved from Shetland connection via Spittal and Blackhillock substations using the Caithness-Moray HVDC link, and from the Western Isles through Arnish, Beauly, and Blackhillock substations using the HVDC link (see Figure 11). Reactive power compensation devices might be required at the onshore substations (e.g. Arnish, Spittal, Beauly, and Blackhillock) to enable the energisation of the AC transformers and transmission circuit connections to the Peterhead substation, from Shetland and Western Isles.

The pumped-storage hydroelectric power station at Foyers (with its existing BS facility) may play an important role to act as an anchor generator to provide a strong AC voltage and inertia support for the Western Isles wind farms through the existing AC 132kV circuit (see Figure 11). The power generated at the wind farm can then be exported to the mainland through the 600 MW HVDC link to support the later stages of system restoration.

For normal operation, the control mode of Western Isles HVDC terminal at Stornaway could be originally used in grid-forming control mode to create an AC voltage for the Stornaway wind farm, and progressively transitioned to PLL-based active power control mode, following synchronization to the 132kV AC network. If the Stornaway Wind Farm could provide Black Start services to the GB grid, then the HVDC converter station at Stornaway would use DC voltage control.

4.2 HVDC Black Start Service in England North-West/East Zones

North Sea Link HVDC scheme

The technical capability of the NorthConnect HVDC link could be applicable to the HVDC North Sea Link (NSL) to provide a Black Start services for the England North-East Zone. The Blyth converter station could be energised from the remote converter station in Norway. The Blyth converter can then operate with grid-forming control mode and be used for re-energising predefined AC transmission corridors to bring more key generation and block loading in the zone. The NSL Blyth converter station may also be used to provide a Black Start services for the Scotland Zone by energising the 400kV transmission circuits between Blyth and Strathaven substation, and onwards via the 275kV transmission circuit to Cruachan power station (with BS facility).

4.3 Summary

This section concludes that Black Start through HVDC schemes in Scotland and North of England Zones is technically feasible, if the appropriate control solutions are implemented. The planned cross-border (NSL and NorthConnect) HVDC interconnectors between GB and Norway can be considered as the most promising source of potential BS services across a total black out event in comparison to the other HVDC schemes connected to the Scotland and North of England Zone. The interconnectors are connected on the Norwegian side to a rich area of hydroelectric power plants which are mature and suitable technologies for Black Start services and can be turned on and off quickly.

The NorthConnect interconnector will be connected at Peterhead in Scotland and could form a multi-infeed HVDC scheme with the future Eastern HVDC link. This could potential facilitate Black Start energization of Peterhead substation from the hydro power stations in Norway, and enable quicker energisation of the Peterhead power station. Other areas of GB could also be energised from Scotland via the proposed 2GW Eastern HVDC links to the Midland's area. The NSL interconnector can also support faster restoration of the North of England Zone and Scotland Zone.

Therefore, it is very important to ensure that future key HVDC interconnectors (e.g. NorthConnect, NSL links, etc.) implement the control and protection schemes required for enabling Black Start services at the design stage, and test their BS performance during the commissioning stage. This will ensure that Scotland and North of England zones maximise the benefits of the future HVDC interconnectors to be hosted within these zones.

The Island HVDC links to Shetland and Western Isles will provide access to almost 1.2GW of renewable generation (mainly wind). It is relatively challenging to implement a full Black Start service from the islands to re-power the mainland grid following a total system shutdown event. This is due to the technical limitation of wind generation to provide sufficient reactive power and frequency support required for reliable operation of a dead network. One option is to rely on the concept of an anchor generator that can help wind farms to participate in system restoration [56]. In the Scotland zone case, the hydroelectric power station at Foyers is connected to the Western Isles network through a 132kV AC network. Hence, Foyers could potentially act as an anchor generator for the proposed wind farms in the Western Isles, thereby providing the required reactive power and rotating inertia to enable the wind farms contribute to system restoration.

5 Global Review of HVDC Contribution to Black Start and System Restoration

This section discusses existing experience and readiness of HVDC technologies to support Black Start services at different stages of system restoration. These include:

- Starting-up one converter terminal when the other terminal is energised to create an AC voltage for a dead network;
- Re-energising associated ac buses, transformers and long AC transmission lines;
- Solely supplying and operating islanded networks without local generation; and
- Providing auxiliary power to remote thermal power plants.

5.1 East-West HVDC Interconnector (EWIC Ireland – GB)

The capability of the EWIC interconnector scheme (see Figure 12) to provide a Black Start service to start-up a remote 300MW non-Black Start coal-fired generation unit was tested using a field trial on the Irish grid during commissioning of the scheme. The trial test steps are given in detail in [43], and summarised as:

- Disconnection of the Moneypoint generation station from the main Irish grid;
- Isolation of about 230km of the Irish 400kV transmission network from the Portan (originally named as Woodland) sub-station (location of the BS converter station) to the 300MW coal-fired generator unit at Moneypoint;
- Energisation of the EWIC HVDC link at rated DC voltage (±200kV) from the GB terminal (healthy terminal), with the main circuit breaker opened at the Irish terminal;
- The EWIC converter station on the islanded side (at the Irish terminal) was set automatically to voltage-frequency control mode;
- Energisation of the interface transformer at Portan HVDC terminal to allow the converter station auxiliary loads to be supplied from a tertiary winding of transformers rather than back-up sources;
- The main EWIC AC circuit breaker on the Irish terminal was closed and 400kV transmission circuit, and the associated transformers and shunt reactors were successfully energised. The EWIC automatically picked up the reactive and real power (losses) demand during this energisation phase;
- Up to 20MW auxiliary loads of the coal generating station was successfully supplied at the remote end, allowing the generator units to start up and run up to its nominal speed;
- Synchronisation of the 300MW generator with the Irish grid was successfully achieved; and
- Automatic transition of the EWIC converter station to power export mode was demonstrated.

The trial was successful, thus enabling the demonstration of the EWIC scheme to provide Black Start services on the Irish network. Currently, the owners of EWIC run an annual test of the Black Start procedures, to maintain the training level of the operators for this essential function [43].

As concluded in [43], there is a great opportunity for the EWIC BS capability to be likewise applied on the GB grid side (Shotton converter station). This will provide a controllable power source of 500MW and ±175MVar which can potentially be considered as a BSSP if the required BS facilities are implemented at Shotton terminal. To enable this, the studies outcomes reported in [43] have recommended that further studies are required for the GB network to establish the regions of the network in North Wales, and North-West England which could be restored from the EWIC (e.g. transmission lines up to 300km from the Shotton converter station).

The studies could also consider several circuits to be energised simultaneously to reduce the restoration time, and consider the need for power station auxiliaries to re-power targeted non-Black Start generation units (energised from the EWIC link). Under this emergency case (EWIC BS to the GB grid), the EWIC link needs to be able to transfer active power of up to 500MW to the GB grid. This may require backup generation on the Ireland side to ensure that full export capacity of the converter is utilised [43].

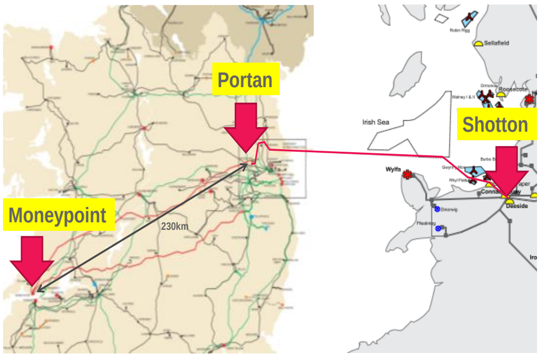

Figure 12: EWIC HVDC Scheme and Moneypoint Coal-Fired Generation Station Locations [43]

5.2 Norway-Denmark Skagerrak HVDC Interconnector

Currently, there are four HVDC interconnectors (named Skagerrak 1-4 and shown in Figure 13) installed between Norway (Kristiansand substation) and Denmark (Tjele substation Jutland) [47]. Skagerrak 1-3 interconnectors were installed in 1976, 1977 and 1993 respectively, and they are LCC-based technology. Skagerrak 4 HVDC interconnector was commissioned in 2014 with power transfer capacity 700MW, and utilises VSC technology. During the commissioning of Skagerrak 4, a Black Start capability test of the scheme was performed on a small islanded AC network disconnected from the Nordic AC main grid.

The test network included the Skagerrak 4 HVDC link with two VSC converter terminals, redundant 132km 300kV transmission line (between Kristiansand and Feda in Norway), three transformers, and 90MW and 36MVAr of equivalent loads (three silicon furnaces and three capacitor banks respectively connected at the end of the transmission line). The main aim of the Black Start test was to assess the capability of supplying the 90MW power load in Norway from a supply in Denmark using Skagerrak 4 HVDC link. The test was led by the transmission system operator (TSO) dispatch Centre in coordination with the silicon furnaces control centre considering the following procedures [47]:

- The Skagerrak 4 HVDC link was energised by closing the AC breaker on the Denmark terminal, and converters terminals were de-blocked automatically and energised the AC grid terminal of the Skagerrak 4 on the Norway side;
- The Norway Skagerrak 4 converter operated in an islanded mode to control frequency and voltage of the islanded test network;
- The 132km 300kV overhead transmission line to Feda substation was energised; and
- The silicon furnace loads were then connected to the islanded grid at Feda substation, and gradually ramped up to full load (about 90 MW) and ran for 75 minutes, and then the three capacitor banks rated 3x12 MVAr were connected.

The outcomes of this Black Start test have proven the capability of a cross-border VSC-based HVDC interconnector (as shown in Figure 13) to create a strong AC voltage supply at its terminal which successfully supplied an islanded dead network with considerable amount of active and reactive loads.

The VSC-based converter station provided a powerful and fast voltage control which significantly reduced voltage transient impacts during the energisation and expansion phases of the network restoration process. The Skagerrak 4 interconnector was tested to supply up to 12% of its rated capacity (700MW). However, it was reported that the interconnector's full power transfer capacity can still be utilised to support the associated AC grid during Black Start system restoration [47].

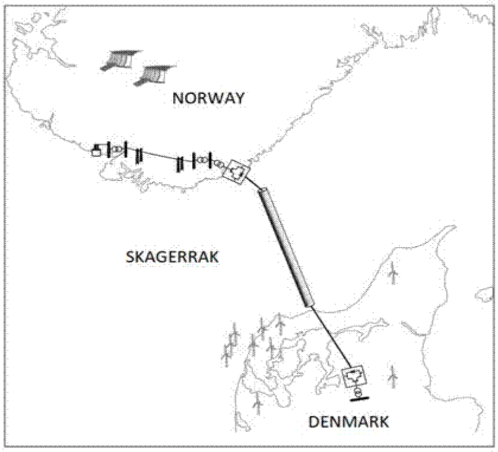

Figure 13: Skagerrak 4 HVDC Link with Black Start test Grid [47]

5.3 Caithness-Moray Commissioning Experience

The GB embedded Caithness-Moray HVDC link (illustrated in Figure 14) utilises VSC technology. One of the reasons for using VSC technology was reported to be the support of Black Start and system restoration capability. During the final stage of commissioning the scheme in 2018, the link was successfully tested for energising a clean busbar in 275kV AC substation as a part of Black Start functionality. The HVDC link terminal at Blackhillock in Moray (close to Peterhead Power Station) was connected to the main grid. The DC circuit of the HVDC link was energised from the Blackhillock terminal, and the converter station at Spittal substation provided the required AC voltage for re-energising the clean busbar at the Spittal 275kV AC substation [52].

Figure 14: Caithness-Moray HVDC Link [57]

5.4 LCC HVDC Black Start with Synchronous Compensators

Unlike VSC HVDC technology, LCC-based HVDC schemes normally require synchronous compensators for starting-up during Black Start conditions without local generation or a strong AC grid available. The synchronous compensators provide the required reactive power and AC voltage regulation capability on the AC side of the LCC terminals to support its converter's commutation.

However, the synchronous compensators do require external power supply to start-up and energise them to their nominal speed that is required to provide the excitation requirement for reactive power control. The LCC HVDC start-up capability supported by synchronous compensators and without local generation has already been tested and demonstrated using Gotland-Swedish mainland LCC HVDC link (see Figure 15). The following procedures were considered [33]:

- An adequate auxiliary power to the LCC converter station was established by using a small diesel generator;
- Starting motors to drive the synchronous compensators were then energised and the required excitation for commutation AC voltage was provided;
- With adequate commutation voltage provided by the synchronous compensators, the associated LCC station was de-blocked in frequency control mode;
- The starting motors disconnected once the compensators brought up to their synchronous speed;
- The HVDC link was then able to supply the running power to the synchronous compensators and its own auxiliary power, with no further requirement for the diesel generators;
- With the synchronous compensators online, the relevant AC lines and substations of Gotland were energised, and allowable loads picked up. This procedure was specifically required to be performed within 5 minutes to limit the operation of the LCC with discontinuous current due to zero/small power load to avoid any potential commutation failure during the BS sequences;
- The islanded operation without any local generation was enabled by meeting the reactive power and AC voltage requirements by the synchronous compensators, and the frequency stability requirements through the imported power from the Swedish mainland and the inertia of the synchronous compensators; and
- The energised LCC terminal and the associated synchronous compensators then provided a start-up power to other Gotland local conventional generation and for wind turbines in the area.

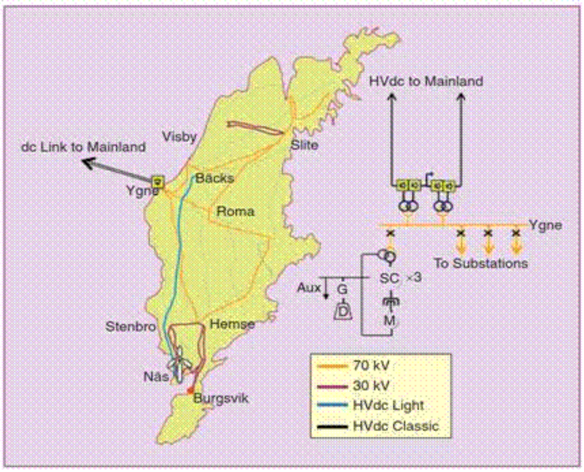

Figure *15*: LCC Gotland HVDC Black Start with a Synchronous Condenser [33]

6 International Black Outs Experience and GB Black Start Innovation Projects

Across the GB electricity industry, although the GB grid is operated to a set of technical and commercial code to GB, the TOs and ESO also consider international events and continue to review best practice and the options that new technology can bring to the subject of Black Start. This is further supported via the ESO involvement in international organisations such as EPRI [58], CIGRE [59], and ENTSO-E [60].

6.1 GB Low-frequency Event on August 9, 2019.

Britain's most severe loss of power in more than a decade [61] occurred on 9th August 2019, with more than 1 million customers temporarily disconnected from the electricity supply system. It was reported that this was caused by the operation of low frequency demand disconnection schemes, following a severe drop in the systems' frequency after two near-simultaneous power plant outages (the Little Barford combine cycle gas-fired power station, 660 MW, and the Hornsea offshore wind farm, 790 MW) [61]. The event is still under investigation by the industry. An interim and final report have recently been issued by NG ESO [62], and it will be followed by a further reports from the E3C committee and the regulator subsequently [63].

The frequency trace during the event is presented in Figure 16, where the loss of 1430 MW of generation resulted in a frequency drop up to 48.8 Hz, thereby enabling the operation of low frequency demand disconnection schemes to secure the system, as expected. During the event no HVDC interconnector disconnected, with one (Moyle) contributing to the frequency response received during the event, which mitigated its scale.

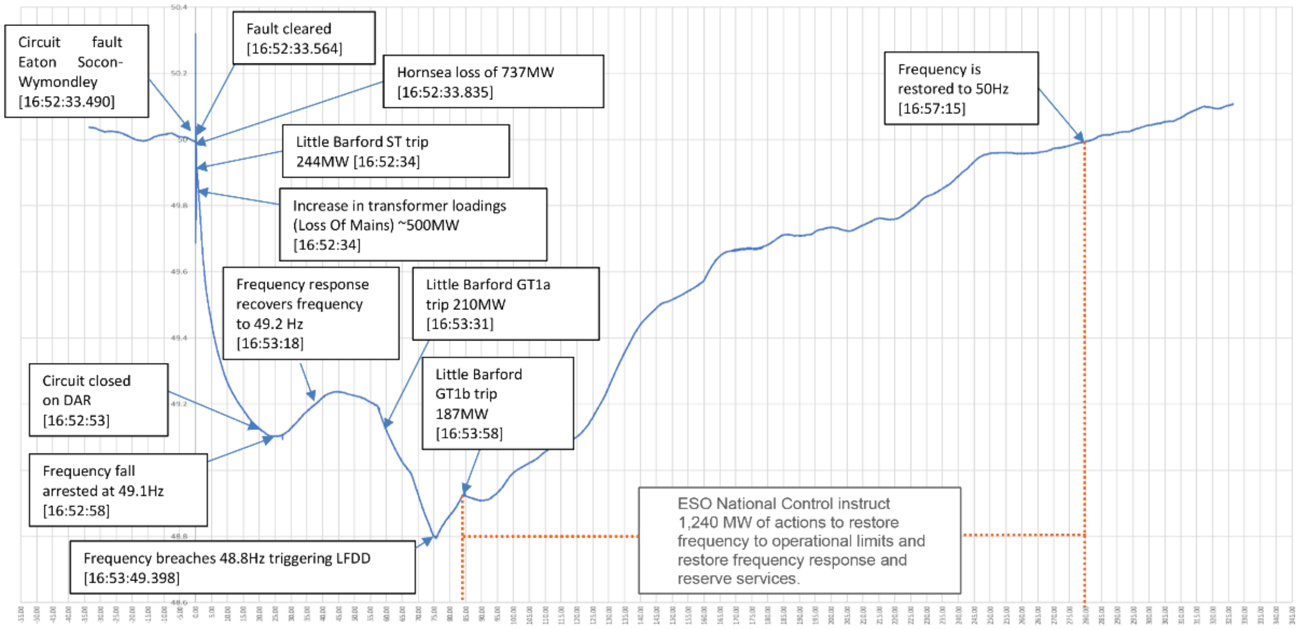

Figure 16: GB system frequency before and after the disturbance on 9th August 2019 [62]

6.2 Recent International Black out Experiences

Table 4 is a summary of international major black out events, followed by a discussion on the role of HVDC links that contributed to restoring power during such events.

Table 4: International Black out Experiences [64]-[69], [70], [71]

Black out Event Type	Country	Date	Cause	Time of Restoration	Effected Customers
Complete	Argentina/ Uruguay	16 Jun 2019	• Two 500kV lines experienced fault conditions. • Two major hydroelectric power plants totalling 2900MW were lost, and further transmission lines experienced further disconnection.	Majority after 12 hrs	Whole countries
System Separation	Australia	25 Aug 2018	• Due to loss of a 330kV AC interconnection from Queensland and New South Wales as a result of a lightning strike on a tower leading to a fault of the two circuits on the tower.		Separation of the system
Partial	Australia	28 Sep 2016	• A storm damaged both a single circuit 275kV transmission line and a 275kV double circuit line. • Nine wind farms reduced power or disconnect in response to a protection function responding to a pre-set limit to the number of ride-through events. • A sustained reduction of a total of 456MW of generation within 7 sec.	90% of the supply restored within 8hrs.	1800MW of load lost
Partial	USA	8 Sep 2011	• Originated from the loss of a single 500kV transmission line combined with lower than peak generation levels. • The system was not operating in a secure N-1 state prior to the event.	12 hrs	Almost 2.7 million people
Partial	USA	26 Feb 2008	• Originated from a delay of 1.7 sec in the clearing of a transmission fault at 138KV, led to loss of up to 22 transmission lines. • Long fault clearance arose from human factors leading to inadequate protection being in place at the time of the incident.	No available information	• Disconnection of almost 3580MW of loads • Trip of 4300MW of generation
Partial	Italy/ Switzerland	28 Sep 2003	• A fault was initiated from a storm, other lines supplying power to Italy from Switzerland were overloaded and tripped. • A series of transmission faults then occurred, arising as a result to foliage growth under transmission lines occurring within Switzerland, close to the Italian border. • A series of further disconnections of transmission lines between France and Italy then occurred.	Approximately 19 hrs	Almost 45 million people
Partial	USA/ Canada	14 Aug 2003	• The event began with a generator fault occurring, led to a series of increase power flow conditions into Cleveland Ohio. • A series of three 345kV transmission lines associated with the power transmission route tripped out of service, as a result of inadequate electrical clearance, these being caused by proximity of the transmission line to vegetation, due to inadequate tree-felling activities. • The loss of the transmission lines drove the cascade loss of a further two 345kV lines driving power onto an underlying 138kV lower voltage system.	Majority within hours, Some areas took 2 days, and in others took further 2 weeks.	Almost 50 million people

At the 2003 Black-out event across North America, within New York City, the Cross – Sound HVDC cable link (a form of VSC-HVDC technology) between New Haven and Shoreham New York was used to restore power to Long Island [72]. During the 25th Aug 2018 system separation event in Australia, the system frequency varied across the range 49-50Hz. An increase in power flow from the HVDC interconnector between Tasmania and Victoria in frequency control, led to a supply deficit in Tasmania and the disconnection of 91MW of interruptible load as part of under-frequency load-shedding arrangements that rebalanced the Tasmanian system in 4 sec after the separation event.

6.3 GB Innovation Black Start Projects

6.3.1 Alternative Black Start Approaches

The GB National Grid ESO completed in March 2015 a review of alternative BS approaches [73]. Two reports with the focus upon the benchmarking of UK & international Black Start Policies and the Black Start Capabilities for Generation & Transmission Technologies were published.

In relation to policies, there were found to be several commonalities of approach internationally, with restoration being broadly split into two types of strategies:

- Top-down strategies with pre- defined corridors of re-energisation of the whole network from external sources (an approach used in certain areas of continental Europe) to supply distribution power;
- Bottom-up strategy building up separated smaller regional power islands in parallel connecting supply as quickly as practicable, synchronising these together as soon as can be allowed (used in GB system); and
- It was also noted a number of specific restoration approaches exist within these two umbrella strategies, for example those defining a strategic “spine” of network reinforcement supporting a Black Start.

The report notes that with the potential growth of Black Start capable interconnectors, noting the promising capabilities of VSC- HVDC technology, increasing consideration of top-down strategies in addition to bottom up could be considered. It states that this would require a number of technical issues (in addition to arrangements to external TSOs for doing so to be considered). These included:

- Management of transient over-voltage during energisation;
- Management of harmonic resonance conditions across longer circuit energisation and subsequent control;
- A question surrounding how intended VSC-HVDC control operates during periods where the VSC HVDC is operating alongside other synchronous generation;
- The need for auxiliary supplies and an ability to support initial energisation, which may require different approaches to that energisation stage;
- Flexibility to a variable size of demand block; and
- The need for new and different test arrangements related to the control approach and plant utilised for energisation, including consideration of the top-down energisation strategies in detail, with particular focus on over-voltage and switching impulse management under the new control strategy.

LCC-HVDC convertors are noted as having limited Black Start capability requiring sizeable (at least 60% of rating) additional synchronous condenser & other compensation capacity to realise.

6.3.2 Black Start from Non-Traditional Technologies

Following the 2015 work (as discussed in subsection 6.3.1), National Grid ESO in January 2019 conducted work to examine three key aspects of the process of Black Start and system restoration from the context of understanding the capabilities and potential for non- traditional technologies to support the Black Start services [74]. These areas involve:

- Power island strength and stability in support of Black Start, considering micro grid power islands;
- Technology capability and readiness level; and
- The effect of a variable energy resource (using a case study of wind variability) on Black Start.

The key issues for future convertor-dominated power islands were found to be high variation of the load and generation being restored, low system inertia, low short circuit level, greater voltage-frequency coupling and dependency, and a loss of earth reference.

Other than lack of earth reference (an issue of medium voltage (MV) distribution design, and associated within MV restoration), all other factors are common across all forms of bottom-up restoration and would require solutions where interconnector restoration methods are explored. Solutions to inadequate power island strength of stability were noted to include; additional inertia, addition of energy storage and fast acting frequency control, adaptive control systems tuned based on the mode of micro grid operation, and changes to protection relays to ensure adequate fault detection. We would note whilst similar control approaches could be explored in large scale convertors, for example interconnectors, the additional challenges of these strategies in larger grid restoration environment is that unlike a micro grid network the status and definition of connected load and generation is much more limited at any given control leading such solutions to be more flexible and adaptive across a broader range of operating conditions.

6.3.3 Black Start from Distribution Energy Resources

The GB National Grid ESO has recently started a three-year project (in Jan 2019) to investigate and trial the capability of utilising distributed energy resources (DERs) to restore electric power to distribution and transmission networks up to 132kV in the event of black out [56]. The project is an Ofgem Network Innovation Competition (NIC) funded project, which aims to develop, design and demonstrate technical, organisational, procurement and regulatory solutions that are required for creating new market access for DERs Black Start services. A number of live trials for testing the DERs potential technical capabilities to act as a Black Start service provider will be conducted. It is believed that participation of DERs in black services will increase the market competition with the potential to reduce Black Start cost and carbon emissions. The net performance value (NPV) of the project is expected to be £115m by 2050 and 0.81MT of CO2 reduction [56].

6.3.4 Battery Storage with Virtual Synchronous Machines for Black Start Application

Virtual Synchronous Machines (VSM) is a technology that utilises advanced power electronic converter controls of non-synchronous generation to provide representative features of conventional synchronous machines. VSM can provide flexible real and reactive power control which can be used for minimising the operational challenges caused by reduced system strengths (reduced inertia and SCL) due to the replacement of conventional generation by renewables. VSM with a battery source can potentially offer other services such as bottom-up Black Start for energising local areas. Recently in June 2019, a new Network Innovation Allowance (NIA) project called 'Demonstration of Virtual Synchronous Machine control of a battery system' started to test the potential of this technology for supporting distribution grid operation including Black Start functionality [75]. The project will run a trial to energise a representative 11/0.4kV distribution network at University of Strathclyde's Power Network Demonstration Centre (PNDC). Black Start test sequences will include, starting the battery-based VSM (0.6MW), energising an LV network, and block LV loads.

7 Recommendations and Conclusions

The potential of meeting the GB ESO Black Start requirements following the changes in the GB power grid nature and strengths would require a combination of conventional (e.g. thermal plants) and non-conventional technologies (e.g. DERs, wind farms, HVDC, etc.). The level of the contribution of each technology to Black Start services depends on their locations, technical capabilities to meet Black Start Grid Code and regulatory requirements, and the cost of the service. This section highlights the key recommendations which could be considered for understanding the technical capability of the GB HVDC schemes to enable fast and reliable GB electricity grid restoration following a complete or partial black outs events.

The National HVDC Centre, commissioned by the Scottish Government, has methodically reviewed how HVDC schemes can be utilised to support Black Start energisation from a Technical perspective (i.e. the commercial and regulatory processes have not been considered); based on this review eight key recommendations have been proposed and discussed with GB Network Owners at a consultation workshop held on 17 September 2019:

1) **Define early specification of HVDC Black Start controls and functional requirements for new projects.** We understand that there would be challenges for HVDC manufacturers and developers to re-engineer Black Start functionality at later stages of project development, whereas allowing future HVDC schemes to specify Black Start functionality at an early stage (for example ensuring black start controls are included in the design) would not necessarily increase costs over those incurred in normal design. Therefore, it would be appropriate for BS control functionality to be a standardised requirement on all future HVDC schemes. The decision to demonstrate the BS capability would continue to be taken at a later stage and would be informed by the National Grid ESO Black Start contract and procurement strategy at that point, with potentially a wide range of cost efficient options available to it than would otherwise have been the case.

2) **Develop extensive and robust whole-system testing and verification processes for network protection systems during Black Start.** Black Start is a highly unusual situation, and we are likely to have very little operational experience of the response of AC transmission network protection (or the HVDC system protection) to faults under the very weak conditions associated with a newly formed power system. It is therefore recommended that the protection settings for both the AC transmission system and HVDC system are extensively tested (as a combined system), for restoration scenarios, including protection systems on distribution networks. We note that the National Grid ESO is currently engaged in work to understand further the options for black start from distribution sources and we believe these recommendations may complement that work.

3) **Carry out detailed Black Start analytical studies of HVDC control systems in Black Start conditions.** The capability of HVDC links to provide Black Start energization and restoration is limited by the converter ratings and control considerations. Hence, significant studies and data exchanges to support them across the industry are required. A further consideration at the later stages of restoration are operational processes and bespoke control strategies to ensure the HVDC link controls transition as expected from Black Start mode to normal operation without tripping. This consideration is most critical when re-energised networks re-synchronise with each other- each potentially having been supported by HVDC.

4) **Develop a detailed commissioning requirement for Black Start provision from HVDC interconnectors that goes beyond Factory Acceptance Testing and includes standardised system testing with real-time simulations and field acceptance testing.** Currently any HVDC Black Start functionality is tested at the factory and this does not give the required level of confidence that it would act as expected on the real network. Therefore, combining factory testing with real-time demonstration and field trials would build confidence in the robustness of the solutions.

5) **Develop a vision for Black Start provision in HVDC-rich areas identifying the role that other devices such as synchronous condensers need to play.** The Black Start services that HVDC schemes provide could be significantly enhanced if combined with other technologies such as synchronous compensators which can increase system strength on a weak power island and provide fault currents for reliable operation of the protection systems in weak grids. Therefore, the role of synchronous compensators and other complementary technologies should be considered for future HVDC schemes.

6) **Ensure that Black Start criteria do not form a barrier to entry forms of technology and service provision.** The System Operator commissions Black Start services from a range of provider, but there are a number of criteria that need to be met to qualify; some of these criteria are not appropriate for HVDC schemes and therefore should be reviewed to ensure that we do not unnecessarily dis-qualify HVDC schemes who could provide valuable Black Start and system restoration services.

7) **Create an integrated training program for control room personnel and operators to implement HVDC-led Black Start.** In principle, electricity control room operators need to communicate with network (Transmission and Distribution) owners and Black Start service providers to restore power to customers. However, inadequate or complex information can increase the risk of incorrect operation across system restoration. Therefore, continuous training of personnel on operation of grids with high levels of HVDC links and other low-carbon technologies, combined with simple, clear and effective communication approaches among all stakeholders is required to ensure reliable system restoration.

8) **Other areas of investigation.** We note that whilst the recommendations above are HVDC focussed as per the centres remit, in principle a number of these above points could have broader application to a range of convertor based technologies- for example Batteries, Solar PV and Wind turbines There are additional possible HVDC Black Start enhancements that merit further investigation; offshore windfarms (or island generation) to help energise the network, and potentially reducing system voltage during restoration to speed-up the time to restore the system.

Table 5 is a summary of the key requirements, recommendations and next steps identified from this report.

Table 5: Summary of key findings, recommendations and future work

	Requirements	Problem Statement	Actions/Recommendations	Organisations	Next steps	Priority
1	**Define early specifications of HVDC Black Start controls for new projects**					
	a. Specification and testing of Black Start Controls	There is a potential for new and adverse interaction between HVDC BS controls and the AC system, which will not be seen under normal operation.	HVDC schemes should be required to specify, test and demonstrate appropriate BS controls to the ESO under a range of credible Black Start conditions.	ESO	ESO to drive actions via Grid Codes and other appropriate forums for implementing guidelines/specifications for Black Start services.	High

	b. Sub-synchronous torsional interactions (SSTI) control damping	Increased risk of SSTI with nearby generators due to HVDC BS, which could damage generator shaft. Generator data is required for SSTI analysis, but this may not be available to third-party.	STI analysis and mitigation tests are required from HVDC schemes across BS operation. Technical data exchange is required between nearby generators and HVDC schemes.	ESO	In addition to 1a above, develop a framework for exchange of data for SSTI investigations, where required.	High
	c. Virtual synchronous machine (VSM) control mode	VSM is an emerging control mode that can enable HVDC links to provide inertia and dynamic voltage support. There is a risk of incorrect operation if VSM control is fitted on existing HVDC links.	Develop specifications for VSM control mode, such that HVDC link can perform flexibly as a synchronous generator within the converter's rated capability.	ESO	Review outcomes of existing ESO VSM expert working group, and ongoing VSM research and innovation projects led by manufacturers and ESO. Commission a specific strand of the VSM working group to examine HVDC Black Start provision.	High
2	**Develop whole-system protection performance testing across HVDC Black Start and weak grid conditions**					
	a. Performance of AC protection	Fault currents seen across HVDC Black Start will be typically lower than normal operation. If settings on AC protection are not verified and tested, there is a risk that protection systems either does not operate or operates more slowly than expected.	Further analysis using electromagnetic transient (EMT)-based assessment of protection function including real-time simulation.	**EPRI, TOs, HVDC Centre**	Build up on ongoing EPRI/HVDC centre investigations on protection studies to verify AC protection system performance across HVDC Black Start and system restoration. Inform options for AC protection changes, where required	**High**
	b. HVDC fault-ride through capability	There is a potential for more severe fault ride-through conditions to occur during BS, which are outside of the requirements for HVDC schemes and could lead to unintended tripping of the HVDC link.	Based on understanding of protection clearance times available during BS, repeat HVDC fault-ride through test analysis/simulations.	**EPRI, TOs, HVDC Centre**	Review HVDC fault ride through requirements across the different stages of Black Start, restoration and sequential start-up following a trip.	**Medium**
3	**Carry out details analysis for managing the extension and growth of HVDC-led power islands**					
	a. Complementing nearby energy sources with HVDC capability.	Other BSSPs can be complemented by the system restoration capability of HVDC links operating in STATCOM mode, if far end converter of the HVDC link is dead.	Compatibility of the appropriate controllers on HVDC schemes and nearby energy sources including battery storage or synchronous generators should be tested to avoid improper control performance.	**TOs, ESO, Black Start Providers (BSSP), HVDC owners.**	Investigate whole system Black Start and restoration case studies informed by local joint restoration plans, involving appropriate exchange of data.	**High**
	b. Re-synchronisation of HVDC BS system with a larger power island	Significant studies are required to verify that the HVDC controller transitions as expected from BS mode to normal operation, without tripping during re-synchronisation to the rest of the network.	HVDC link requires an input signal to order a transition between BS and normal control mode. The length of time delay between the controller transition may require careful consideration or field adjustments to minimise risk of mal-operation.	**TOs, ESO, EPRI, HVDC Centre.**	Review outcomes of ongoing projects on HVDC energisation led by EPRI/HVDC Centre and network innovation competition project on Distributed Restart led by TOs and ESO.	**High**
	c. Synchronisation between two HVDC-led power islands	The flexibility of the HVDC schemes to control a power island is limited by its rating and control considerations. At later stages of BS, coordination of frequency control duty is required between two adjacent HVDC-led power islands.	Develop a framework for exchange of data required for analysis of the later stage of BS restoration and synchronisation between two different HVDC-led power islands.	**TOs, ESO**	Consider specific case studies involving two or more HVDC-led power islands, informed by Local Joint Restoration Plans and examine appropriate BS control options, transitions and synchronisation arrangements.	**Medium**

4	**Develop detailed commissioning requirements for HVDC Black Start, including field trials and system tests to increase Technology Readiness Level (TRL)**	**Currently, any HVDC BS functionality is tested at the factory, Additional forms of demonstration suitably complemented by physical tests/field trial, are required to establish all the above performance areas on future HVDC BS services.**	**Following the outcome of the above analysis, framework of new tests and requirements should be developed and then demonstrated on new projects.**	**ESO, TOs**	**Once above investigations are complete, summarise overall requirements in stages of testing necessary. i.e. offline simulation, real-time simulation, field trials, factory acceptance tests and appropriate test injections.**	**High**
5	**Develop a vision for Black Start in HVDC-rich areas to identify role that synchronous compensators and other technologies can play**					
	a. VSC	The ability of VSC to support BS is limited by its rating. Synchronous compensators and other technologies can contribute to system strength and fault currents in HVDC-led power islands and weak ac grids, where required.	TOs to investigate the potential benefit of complementing VSC HVDC BS solutions with synchronous compensators for improving system restoration and grid strength. Also, TOs should examine the options for protection change versus synchronous compensators on a case by case basis.	**TOs**	As part of LJRPs, TOs conduct specific analysis to allow the possibility of VSC HVDC restoration complemented by synchronous compensators and other technologies. ESO stability pathfinder project may provide additional technology options.	**Medium**
	b. LCC	LCC inherently requires a strong system for reliable operation, and to participate in BS, synchronous compensators of a scale significantly higher that the size of HVDC link would need to be installed.	Given the limited potential for new LCC development there would not appear to be a requirement to explore this option further at this time.	**TOs**	Whilst the potential for BS provided by LCC is limited, it should be kept under review.	**Low**
6	**Ensure appropriateness of Black Start technical requirements and their definitions to avoid barriers to entry to new forms of technology, including HVDC**	**Current approach to BS is driven by historic availability of conventional generation source. Based on the flexibility of HVDC and other BS solutions, it may be appropriate to define different requirements at different stages of BS to ensure the maximum participation from available resources.**	**Based on findings of studies above, and any information provided under current BS tendering activity conducted a review of technical requirements for HVDC BS.**	**ESO**	**The use of a bottom-up strategy only, time to connect, and service availability are examples of areas that could be reviewed. HVDC solutions have less auxiliary load requirements and warming arrangements would be different to conventional generation.**	**Medium**
7	**Create an integrated personnel training programme with testing of effective Communication approaches**	**Inadequate training or complex information exchange between control room operators, network owners and black start service provider could result in unsuccessful system restoration.**	**Control room operators would require continuous training on operation of grids with high level of HVDC links, combined with simple, clear and effective communication with TOs and HVDC BSSPs.**	**ESO, TOs, DNOs, HVDC Owners, and Black Start Service Providers.**	**Across the industry, network operators should review whether new areas of training may be applicable to improve coordination and communication across Black Start and system restoration.**	**High**
8	**Other considerations**					
	a. Self-starting Offshore Wind farms or AC island	At present, there is limited demonstration of the capability of offshore ac grids or wind farms to contribute to BS.	Explore the practical possibility of back-energization using the example of Shetland network either from wind or from the proposed HVDC link.	TOs, Offshore Wind Farm Developers	Review findings from NIC on DER Black Start combined with further work from PROMOTION project and OFTO Group.	Low
	b. Operation at Reduced voltages (operating network at lower voltages to reduce the reactive power requirement)	The limited rating of HVDC links can be mitigated by reducing the operating voltage of the network being energized in principle, but this might lead to other network security issues in practice.	TO would need to investigate the resilience of network at a lower operating voltage. The consequence of this would need to be agreed on the DNO system.	TOs, DNOs	Review the opportunities to do this using the LJRPs. This would only be valuable in situations where it is impractical to support restoration using normal procedures.	Low

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