Black-Start of HVDC-Connected Offshore Wind Generators for System Restoration

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***Abstract*—With the increasing integration of inverter based renewable energy resources, the inertia of the power grid has been greatly reduced. This can lead to power outages or even widespread blackouts in extreme situations. In order to mitigate these severe consequences, it is crucial to develop effective black-start and system restoration strategies. This paper aims to study the challenges of using HVDC-connected offshore wind generators (OWGs) as a black-start resource for system restoration and develop a comprehensive solution. The developed solution includes the black-start of the OWG, the energization transient analysis and black-start control of the HVDC connection, and the network rebuilding for system restoration. A simulation study is performed by using HVDC-connected OWGs as a black-start resource to energize nearby transmission lines and build a local grid. Through a comparative case study, the simulation results show that the VSC-HVDC control can effectively provide frequency and voltage control to avoid possible overvoltage and stability issues during system restoration.**

Keywords*—*Black-start; VSC-HVDC; offshore wind generators; modular multilevel converter (MMC); system restoration.

I. INTRODUCTION

To accelerate grid decarbonization, many countries have issued strong incentives to significantly increase the installation of renewable energy resources, including offshore wind. The United States (U.S.) government has set an ambitious target to install offshore wind generators (OWGs) of 30 gigawatts (GW) by 2030 to exploit the vast potential offshore wind power and contribute to the net-zero emission goal [1-2]. The output of large-scale, long-distance offshore wind farms is usually transmitted via the voltage source converter-based high voltage direct current (VSC-HVDC) to onshore power grids [3]. In the existing literature, the VSC-HVDC is considered the most effective solution due to various techno-economic advantages of fast and independent control of active and reactive power, the feasibility of multi-terminal dc grids, and black-start capability [4].

The integration of the flexible and high functional VSC-HVDC system provides new opportunities to support the operation of onshore power grids in various conditions, including system restoration that follows with a major power outage or the worst-case scenario, i.e., a blackout [5-6]. The power outage/blackout can be caused by numerous factors, such as natural disasters, deliberate sabotage, power system instability, human errors, or unexpected losses of major generating units and/or loads [7-8]. Their consequences could be disastrous. In recent years, several blackouts have been reported, such as the 2016 South Australia blackout [9], the 2019 United Kingdom [10], and especially the recent 2021 Great Texas Blackout that caused a loss of $195 billion [11]. To mitigate the consequences, appropriate restoration actions must be taken to bring power grids back to normal in a safe and efficient manner and enhance the resilience of power grids [12].

A part of the power grid experiencing an outage is usually restored with the assistance of its neighboring power grids via the connected tie lines [13]. When the power grid encounters a widespread blackout, its system restoration must begin from pre-selected generating units with the ability to start themselves, i.e., black-start units. The restoration starts from a black-start unit and picks up the critical system loads step by step. To speed up this restoration process, the black-start procedure is carried out simultaneously by multi pre-selected generating units independently. The resulting established independent islands with generating units and loads will be later synchronized to restore the entire power grid [14]. The inherent characteristics of integrated VSC-HVDC connected OWGs, such as flexible control and black-start capability, make them good candidates for black-start units in the future power grid. With the increasing penetration of offshore wind power, the topics of using HVDC-connected OWGs as a black-start resource for system restoration have attracted increasing attention. However, the research has not been explored systematically due to the long-standing gaps between power systems and power electronics. Only several studies discussed the related topics [4-5, 15-17].

The previous study in [15] firstly discussed the black-start capability of a grid-connected VSC-HVDC system and used a charged dc capacitor that is connected with the VSC as a standby black-start resource for system restoration. The work of [5, 16-17] used a diesel generator or a large battery energy storage system (BESS) located at the offshore or onshore VSC station as a standby start-up facility to energize an offshore wind farm (OWF). Under the normal operation mode, the wind farm side VSC (WFVSC) of the HVDC usually applies a grid-forming control to control the offshore ac side voltage to enable the collection of all offshore wind power [4]. The grid side VSC (GSVSC) uses a grid-following control to maintain its dc voltage at a constant level to deliver all the received power and control the voltage of the power common coupling (PCC) at an expected level [4]. However, the grid-following GCVSC cannot enable the HVDC system to support the grid voltage and frequency during system restoration. The study in [16] reported a black-start control strategy that exchanged the control schemes of the GSVSC and WFVSC in the normal operating mode. As a result, the HVDC-connected OWF functioned as a grid-forming resource to support the system restoration of the onshore ac grids. Specifically, the offshore WFVSC used the grid-following control to regulate the dc-link voltage and reactive power output to the offshore ac grid, while the GSVSC applied the grid-forming control to control the voltage and frequency of the onshore ac grid actively. A droop-based control strategy of a multi-terminal VSC-HVDC (MTDC) system has also been developed by the author in a project funded by the European Commission [3-4, 22]. This control strategy enables

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offshore wind farms to provide frequency regulation for the onshore grid. However, this study does not involve black start applications.

With the development of power electronic technologies, the modular multilevel converter-based high voltage direct current (MMC-HVDC) system has become one of the most competitive solutions to the long-distance interconnection of power grids and the integration of large-scale renewable energy resources [18]. Compared with the two- or three-level VSCs, MMCs exhibit techno-economic advantages, such as high modularity and excellent output waveforms [19].

Following this trend, the study in [17] expanded the black-start control strategy of the VSC-HVDC in [16] and applied it to the MMC-HVDC. However, both studies in [16-17] used a diesel generator to pre-charge the WFVSC to energize the offshore collection grid, and ignored the potential of the self-start OWGs as a black-start resource. Using the same black-start control strategy, the study in [20] showed that HVDC-connected OWGs using the grid-forming control can be an independent black-start resource without a diesel generator. However, the simulation developed in this study did not investigate the transients caused by the cold load pickup during restoration, e.g., inrush currents. Therefore, it is difficult to demonstrate the capability of the proposed HVDC control for system stabilization during restoration. In addition, this study only focuses on the black-start process of the HVDC system and did not provide a follow-up solution for the restoration of the bulk ac grid. The energization transients of the MMC-HVDC system have also been studied and corresponding mitigation strategies using a pre-insertion resistor were developed by the author [23-25]. These studies can benefit the black-start of the MMC-HVDC system. However, it does not involve the black-start process.

These existing studies primarily discussed the possibility of the system restoration using HVDC-connected OWGs as a black-start resource under simple simulation scenarios. Many challenges on this topic remain unsolved. Particularly, the most important issue during system restoration is overvoltages that can activate protective relay operations, damage high-voltage equipment, and induce lighting arrestor failures, especially in weak ac grids. Therefore, voltage control is a critical task during system restoration. The traditional black-start generators, such as steam turbine generators, can absorb/send reactive power from the system to achieve the terminal voltage control due to the excitation regulation. However, this voltage control is very slow due to a large time constant of excitation systems (about 0.5 s). It cannot be utilized to suppress fast transient overvoltages when energizing a transmission line during system restoration. In contrast, the HVDC-connected offshore wind farm can provide fast regulation of reactive power output to control its ac terminal voltage based on the pulse width modulation (PWM) technology. Therefore, the reactive power control of the HVDC can be applied to suppress potential overvoltages during restoration if an HVDC-connected offshore wind farm is used as a black start unit.

Currently, existing studies still lack a persuasive and comprehensive solution to study the system restoration using HVDC-connected OWGs as a black-start resource and corresponding transient behavior. To contribute to this area, this paper develops comprehensive and systematic black-start and restoration strategies using HVDC-connected OWGs as a black-start resource, including the black-start of OWGs, HVDC energization, HVDC black-start control, and system restoration. A case study is performed in the paper to evaluate how the VSC-HVDC control strategy benefits the system restoration. Specifically, the study compares the case using HVDC-connected OWGs to energize a nearby transmission line and build a local grid, with that using OWGs without an HVDC link under the same scenario. The simulation results show that the HVDC control can eliminate overvoltages during energization effectively and improve the system damping to mitigate possible stability issues during system restoration.

II. Proposed Black-start and Restoration Strategies

Fig. 1 shows the configuration of an OWF that is connected to an onshore ac main grid via a point-to-point VSC-HVDC link. When a power outage or blackout in the main grid is detected by the control and protection system of the onshore station, the converters are blocked immediately and the PCC circuit breaker is disconnected. Afterward, the HVDC-connected OWF is switched to the black-start control mode for system restoration.

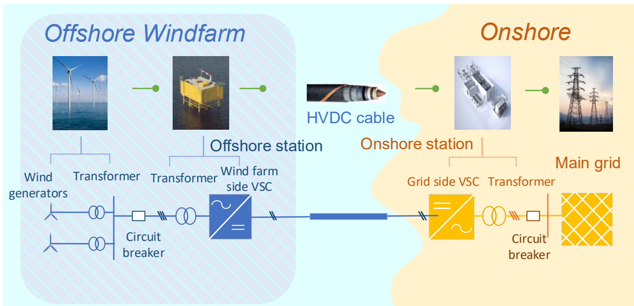

Fig. 1. Configuration of HVDC-connected OWF

This paper discusses the potential of the OWG as a black-start unit and proposes a system restoration strategy that uses black-started doubly-fed induction generators (DFIGs) to energize the HVDC system. Also, the system restoration of a local ac grid and its synchronization to the upstream grid is discussed to guide future research.

A. Using OWGs as a black-start resource

The doubly-fed induction generators (DFIG) is widely used for wind farms due to their voltage control flexibility, and better fault ride-through capability [24-26]. In this paper, the DFIGs will be used for the OWGs as black start units. Particularly, they will utilize a battery energy storage system (BESS) connecting in parallel with their dc link to compensate for the intermittency of wind power generation. After a blackout, the BESS can be used to provide power support for starting up the DFIGs.

B. Energization of HVDC system

After the startup of the OWF, the offshore circuit breaker is closed, and the HVDC system components including the offshore transformer, WFVSC, HVDC cable, GSVSC, onshore transformer, and the export cable will be energized in sequence. Here, MMC technology is considered to investigate the energization transients of the VSC-HVDC system.

Fig. 2 (a) shows the configuration of a half-bridge MMC. As seen, each submodule in Fig. 2 (a) contains an insulated gate bipolar transistor (IGBT) half-bridge as a switching

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element and a capacitor unit for energy storage. During the energization of an MMC-HVDC station, the power converter is required to be blocked. That is, both IGBTs in each submodule are switched off. When the WFVSC is connected for energization, the current flows from the offshore ac terminal to the positive dc pole to charge the capacitor. If the current flows in the opposite direction, the freewheeling diode D2 bypasses the capacitor, as shown in Fig. 2. As a result, the converter during the status of energization becomes a diode bridge. In this circuit, the switching operations of the diodes depend on the instantaneous voltages at the ac side of the converter. The caused natural diode switching behavior generates unexpected lower-order harmonics. Differing from the two or three-level voltage source converter (VSC) based HVDC, the MMC-HVDC station is not equipped with an ac filter. These lower-order harmonics can cause the saturation of the offshore transformer, resulting in inrush currents and voltage dips at the OWF bus. These can activate the protection system of the OWF, impact the operation of the OWF, or even interrupt the black-start.

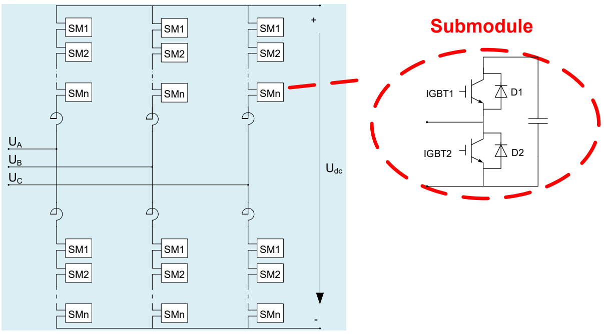

Fig. 2. MMC configuration

To suppress inrush currents during energization of the MMC-HVDC, a mitigation strategy using a pre-insertion resistor has been proposed by the author and the corresponding transient analysis has been conducted in [23-24] through a comprehensive EMT simulation. This mitigation strategy can be applied for the black-start of the HVDC system.

C. Black-start control of HVDC system

The HVDC control is critical for the OWF to provide a black-start service for system restoration as it can provide voltage and frequency regulation for the onshore ac grid. When the onshore ac grid experiences a blackout, the HVDC converters are blocked and disconnected from the ac grid and OWF by opening the circuit breakers CB1 and CB2. The converter control system is automatically switched to the black-start mode. Fig. 4 shows an ac grid with an HVDC-connected OWF. The digital control process will generate a signal of a series of ramps (phi) with the peak value of 2π and pre-determined frequency [27]. This signal acts as a voltage-controlled oscillator for preparing the black-start.

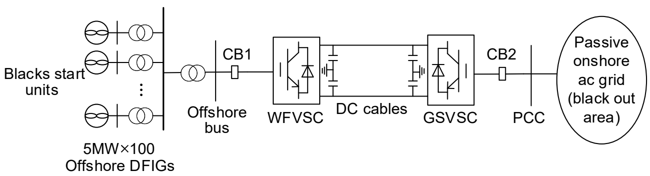

Fig. 3. AC grid with HVDC-connected OWF

In the beginning, the BESS provides reactive power support for the black-start of DFIGs. The offshore wind terminal voltage is gradually increased. When the ac terminal voltage of DIFGs rises to a pre-determined value, e.g., 0.9 p.u., the breaker CB1 is closed. As soon as the offshore wind terminal voltage reaches its rated level, the WFVSC is unblocked to achieve the charging of dc cables. Meanwhile, the OWF is available to provide active power support for auxiliary loads of the VSC station, such as pumps and fans of the cooling system. During the energization of dc cables, the WFVSC is required to control its ac side voltage at an expected level. The time-dependent function phi of the WFVSC is used to identify the voltage reference of the WFVSC ac side.

Once the dc-link voltage reaches its rated level, the GSVSC is unblocked and its ac side voltage is increased. At this moment, the ac grid is a de-energized network. The GSVSC is utilized to control the ac side frequency until the first synchronous generator in the ac grid is started. In addition, the GSVSC can provide reactive power support to maintain its ac side voltage at an expected level. Specifically, the GSVSC applies a constant ac and dc voltage control strategy based on the d, q-axis decoupling control, as shown in Fig. 4. It can regulate its reactive power output to maintain the corresponding PCC voltage (v_{ac}) at an expected level.

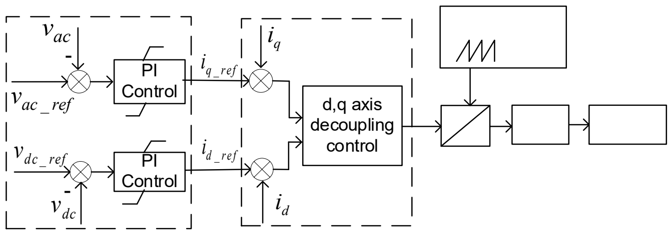

Fig. 4. Simplified control configuration of GSVSCs

As shown in Fig. 4, the error between the reference and measured PCC voltage is used to control the q-axis component of the GSVSC ac side current that determines the GSVSC reactive power output. Its reference voltage can be pre-calculated by the PWM modulation ratio that is determined by the ramp phi. When a PCC experiences a voltage dip/rise, the corresponding GSVSC control is activated to provide/absorb reactive power to boost/suppress the PCC voltage. In order to balance the active power at the sending end and receiving end of the HVDC, the GFVSC will also control the dc voltage at a constant level. When the PCC voltage reaches the level of 0.9 p.u., the circuit breaker CB2 is closed to initiate the restoration of the ac grid.

D. System Restoration

The system restoration plan is defined step by step, based on predefined guidelines and operating procedures. The general restoration procedure includes the black-start of a power plant, i.e., a HVDC-connected OWF, energization of a HVDC connection, and system rebuilding. In this paper, the HVDC-connected OWF is served as a black-start unit to restore the ac grid, by performing the following sequence of actions. It is noted that the HVDC requires various control modes during different periods of system restoration.

1) Building local grid. A HVDC-connected OWF is used to energize nearby transmission lines and loads to build a local grid. During this period, the GSVSC of the HVDC connection applies a constant ac voltage and frequency

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control mode to maintain the grid's normal operation. Its fast reactive power regulation can be utilized to deal with overvoltage issues, which is the most important issue during system restoration that usually occurs when energizing unloaded lines and may activate protective relay operations and/or damage high-voltage equipment. The WFVSC controls the voltage of the dc-link to balance the power flow of the local network. The HVDC-connected OWF and energized lines and loads form a power island. For a large black-out grid that contains multiple HVDC-connected OWFs, the procedure of its system restoration can be sped up by using multiple pre-selected OWFs as the black-start units to perform the black-start process simultaneously and independently. The resulting separate energized local grids can be synchronized and combined into a large island that will be later resynchronized with the upstream grid.

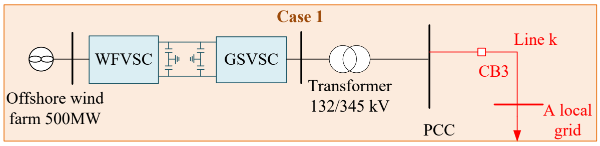
2) Re-synchronization with the upstream network. After forming an island, the local grid needs to be resynchronized with the upstream grid by following the procedures of synchronization. In order to coordinate the local grid with the upstream network during the re-synchronization, the GSVSC is no longer required to provide frequency support. The HVDC control strategy can be switched to the normal power control mode. In this mode, the GSVSC is used to control the dc-link voltage and provide reactive power support for the onshore ac grid to maintain the PCC voltage at a pre-determined level. The references for the voltage and frequency will be switched from the predefined values generated by the control center to the measured values at PCC via the phase-locked loop (PLL). The WFVSC adjusts the magnitude and frequency of the wind farm terminal voltage to enable the collection of offshore wind power.

III. Case Study

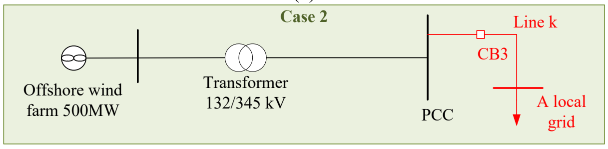
System restoration is especially concerned by the utilities to ensure a resilient and reliable system operation after power outages. Therefore, a comparative simulation study is performed in this section to show the capability of a HVDC-connected OWF during system restoration. Due to the flexible control capability, the VSC-HVDC can control frequency and voltage effectively to avoid possible overvoltage and stability issues, thus providing effective black-start services to ensure a successful system restoration. The case study is performed in simulation software DIgSILENT, including two cases. As shown in Fig. 5, case 1 uses an HVDC-connected OWF with the capacity of 500MW to energize a nearby transmission line k and build a local grid capacity. Case 2 connects the identical OWF with Case 1 to the PCC without a HVDC connection to perform the same scenario. Specifically, line k is rated at 345 kV with a length of 20 km, and the local grid is lumped together and consists of induction motors with the capacity of 100 MW and 25 MVar.

A scenario is performed in Case 1: (1) the OWGs are equipped with BESS and the OWF functions as a black-start unit for system restoration after a major blackout at the ac grid side; (2) the WFVSC controls its ac side voltage and frequency, and the GSVSC uses the constant ac and dc voltages control mode; (3) after energization of the HVDC, the GSVSC uses constant frequency and voltage control, and the CB3 is closed to energize the line k and pick up the lumped local grid. As Case 2 does not have a HVDC link, only step (1) is performed in Case 2 and the OWF uses constant frequency and voltage control to provide power support for the local grid. The simulation results show PCC voltage performance after the switching of CB3 to demonstrate the effectiveness of the HVDC control for regulating the grid voltage and frequency during the restoration process. The simulation results of both cases are shown in Fig. 6 (a) (case 1) and Fig. 6 (b) (case 2), respectively.

The simulation cases are reported here to demonstrate the

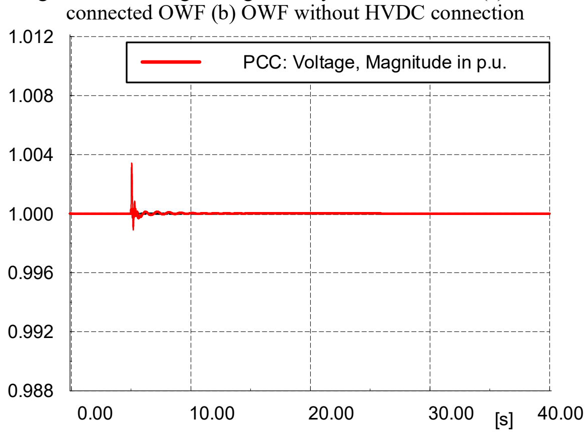


(a)

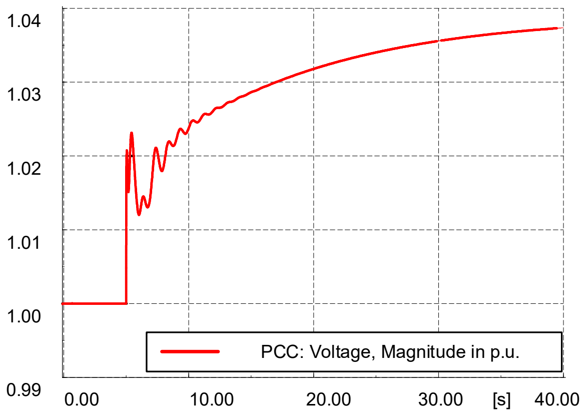


(b)

Fig. 5 Building local grid for system restoration: (a) HVDC connected OWF (b) OWF without HVDC connection



(a)



(b)

Fig. 6 PCC voltage while energizing line k (a) case 1, (b) case 2

HVDC impact on voltage regulations while energizing a loaded transmission line. When a PCC experiences a voltage rise during restoration, say, energizing unloaded or lightly loaded lines, the GSVSC control is activated to absorb reactive power to reduce the PCC voltage. With the high-frequency switching technology, the time constant of the VSC control can be in the order of tens of milliseconds, much faster than that of excitation systems of synchronous generators.

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It is seen in Fig. 6 (a) that the voltage at the PCC increases rapidly after the switching on of CB3 at 5s. Due to the HVDC control, the voltage rise is eliminated immediately and forced back to the normal condition, i.e., 1 p.u.. The voltage rise also appears in Case 2 but with a much higher peak value, i.e., 1.024 p.u., than Case 1, as shown in Fig. 6 (b). The main reason is the reactive power capability of the DFIG, which is about 25% of the capability of the DFIG. Therefore, the OWF in Case 2 does not have sufficient reactive power capability to eliminate the voltage rise during the restoration. In addition, its transient response has severe and long-last oscillations compared with that in Fig. 6 (a). The comparison indicates that the HVDC-connected OWF in case 1 can suppress the overvoltage while restoring a transmission line with a load lump, thus improving the system damping and stability. It also shows in Fig. 6 (b) that the steady-state voltage of the PCC is not restored and maintained at about 1.04 p.u. without the HVDC connection. By comparing both simulations results, it can be concluded that the HVDC black start control can effectively decrease voltage oscillation and alleviate transient and steady-state overvoltages during system restoration. In addition, the HVDC can provide effective frequency control before the synchronization of generators.

IV. Conclusion

This paper identifies the main challenges of the system restoration using a HVDC-connected OWF as a black-start unit. It develops comprehensive, systematic black-start and system restoration strategies. A case comparison with and without the HVDC connection is performed to show the benefits of the HVDC control on the system restoration energization. The simulation results show that the HVDC control can suppress overvoltages effectively and regulate the frequency during the energization transients of the onshore ac grid. This enables the OWF to offer effective black-start services to achieve a safe, smooth, and resilient system restoration.

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