Module 4d: Offshore HVDC Converter grid forming controller design for black start capability

Modules for Maturing HVDC Electric Transmission Knowledge

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Prerequisite Competencies:	1. Introduction to HVDC technology (Module 1a) 2. HVDC control fundamentals and applications (Modules 4a, 4b, 4c)
Module Objectives:	1. Black start capability requirements and challenges for offshore HVDC systems 2. OWFs grid forming controller design and black start strategy for HVDC systems

Abstract

Power systems are transitioning towards decarbonization with the widespread integration of renewable energy sources replacing conventional thermal power plants, the primary providers of black start (B.S.) services. Consequently, conventional B.S. resources may not be available during a total or partial blackout. The offshore wind farms (OWFs) are typically connected to onshore grids with voltage-source-converter-based high-voltage DC (VSC-HVDC) converters and DC cables. These converters have a fast and outstanding voltage and frequency response, thus bearing the capability to reduce restoration time after a grid blackout. They can also precisely control the power flow, which is valuable for gradual and controlled energization of a reviving network during B.S. The grid-forming (GFR) capability is crucial for B.S. operations where the offshore grid must be restored without relying on external power sources/onshore grid. This module will present the challenges and solutions for utilizing OWFs as a valuable B.S. resource. It will differentiate the GFR from the GFL controllers and provide a GFR design and B.S. restoration strategy utilizing OWFs.

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Acronyms

AC	Alternating current
B.S.	Black start
DC	Direct current
GFR	Grid forming
GFL	Grid following
HVDC	High voltage direct current
LCC	Line commutated converter
PV	Photovoltaic
OWF	Offshore Wind Farm
VSC	Voltage commutated converter

4d-1 Introduction

Black start (B.S.) service is the process of restoring power to a grid without relying on an external power supply. These services are becoming more challenging with the integration of new energy resources, particularly renewable energy sources like solar and wind [1]. Conventional power plants, such as coal, natural gas, and hydroelectric, have large rotating masses (turbines and synchronous generators) that provide inertia, stabilizing the grid during a B.S. On the other hand, solar panels and wind turbines are connected via inverters, which do not inherently provide traditional inertia, which makes stabilizing the frequency and voltage during grid restoration harder [2]. Modern inverters with some energy storage can mimic some grid-support functionalities (like synthetic inertia) and be equipped with grid-forming (GFR) capability, so they don't rely on grid voltage for synchronization, which is absent during a B.S. [3], [4]. Another issue with PV and wind generation is that these sources depend on sunlight and wind, which are not controllable or always available. During a grid outage, these resources cannot contribute to B.S. if the weather is unfavorable. However, this issue can be addressed by utilizing on-site energy storage [5].

Conventionally, when a power grid experiences a complete blackout, the restoration process involves the utilization of pre-selected black-start generation units, picking up critical system loads in steps. To reduce downtime, this process is performed by multiple units simultaneously forming restored power islands, which are later synchronized to restore the entire power grid [6], [7]. The typical B.S. process is depicted in Figure 4d - 1.

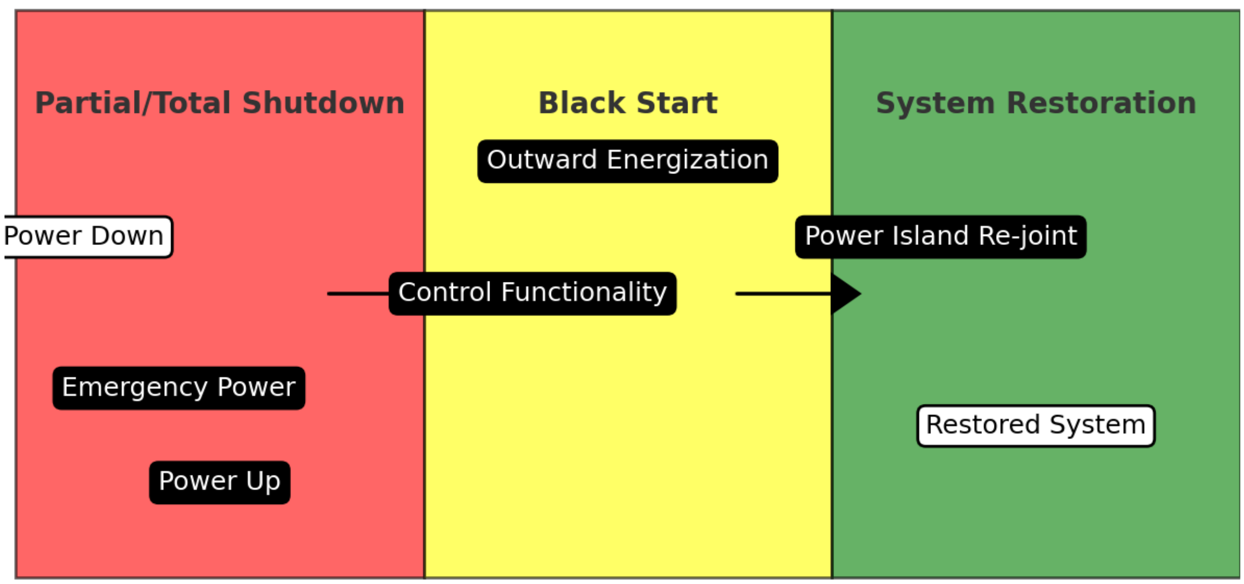

Figure 4d - 1: Typical black start restoration process after grid blackout

The type 3 and type 4 offshore wind farms (OWFs) are typically connected to onshore grids with voltage-source-converter-based high-voltage DC (VSC-HVDC) converters and DC cables. The VSC-HVDC has significant benefits, such as B.S. capability, compactness, ability to integrate into weak AC networks, and independent active and reactive power control [8]. These converters have a fast and outstanding voltage and frequency response, thus bearing the capability to reduce restoration time after a grid blackout [9]. They can also precisely control the power flow, which is valuable for the gradual and controlled energization of a reviving network during B.S. [10], [11].

The three stages of B.S. services provision by OWFs are depicted in Figure 4d – 2 [11].

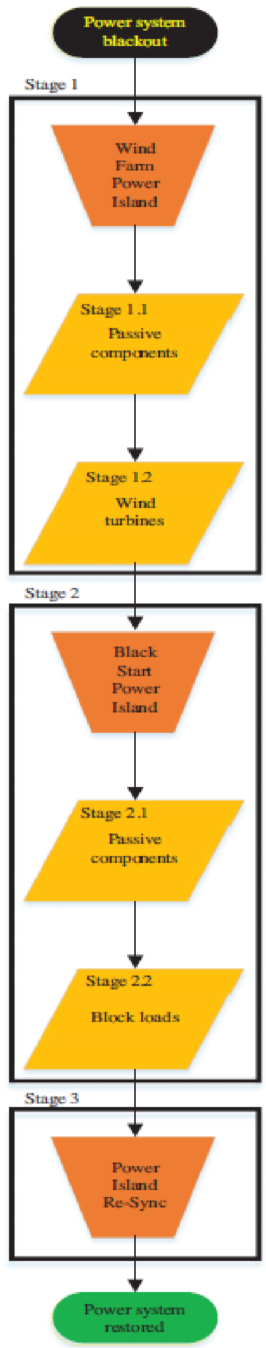

Figure 4d - 2: Black start restoration process utilizing OWFs

INDUSTRY INSIGHT

In the Global Innovation Report published by Hitachi ABB, Atsushi Nishioka, Chairman & CEO of Hitachi ABB HVDC Technologies, Ltd., talks about the present and future of the VSC-VDC [12]. The scripts from the report highlight the importance of VSC-HVDC in B.S. restoration is copied below:

"VSC HVDC can be utilized to support restoration after blackouts. It can energize and supply isolated AC grids with substantial loads. Live full-scale black-start has already been performed and it shows that the basics of the VSC HVDC black-start functionality works as intended, i.e. VSC converters have the ability to build up, stabilize, support, and supply a blacked out islanded grid with a significant amount of load. This will greatly speed up the restoration process after a major black out. However, there are important lessons learned and pre-conditions to consider. It is very important that transmission system operators (TSOs) and HVDC contractors prepare a black-start procedure, which is safe, easy, efficient, and possible to execute during a major blackout."

Atsushi Nishioka

Chairman & CEO, Hitachi ABB HVDC Technologies, Ltd.
Current work and research: HVDC projects in Japan. Society memberships: The Institute of Electrical Engineers of Japan (IEEJ).

This module will present the challenges and potential solutions for integrating B.S. services into OWFs in Section 4d-2. Section 4d-3 will focus on differentiating GFR from traditional grid-following controllers (GFL) and the importance of GFR in providing B.S. services for offshore HVDC systems. It will introduce a GFR controller design followed by a B.S. restoration strategy for offshore HVDC systems in Section 4d-4. This module will conclude by providing a summary of the introduced concepts in Section 4d-5.

The individual sections discussed above are presented below.

4d-2 Challenges and potential solutions for integrating black start services into OWFs

The blackouts of the grid could occur due to natural disasters, instabilities in power systems operations due to grid faults or unexpected loss of generating units [13]. Once the grid is down, it is typically restored with the help of neighboring healthy power grids through the tie lines [14]. The OWFs, with their significant capacity and fast controllers, hold potential as innovative B.S. units, necessitating a new design for OWFs [15].

The units committing to B.S. services provision must meet certain requirements before being qualified as a B.S. unit by the transmission system operators (TSOs). These requirements are listed below:

1. Self-start capability
2. Duration of service availability
3. Inertia
4. Control and interoperability
5. Dynamic response
6. Harmonics

The individual challenges discussed above and potential solutions to address these challenges to utilize OWF as B.S. resource are discussed below.

4d-2.1 Self-start capability

The WTs are inherently powered up by the wind, which is a variable resource and might not be available during the grid restoration process after a complete blackout. If wind is available, the WTs still need some initial power to activate their auxiliaries. Several options could be utilized to introduce the self-start capability into OWFs essential to provide B.S. services. These options are discussed below:

- *Onsite diesel generators*

The diesel generators located at offshore substations could be utilized to restart the larger OWFs by powering up their auxiliaries [16]. These diesel generators could be turned off when a sufficient number of turbines have been restarted. Later, the powered-up turbines could be utilized to power the other turbines in the OWF. In this case, the WT controller should be capable of operating in the GFR mode. A centralized OWF controller could be utilized to manage all these procedures. A larger substation diesel generator could also be replaced with a small diesel generator located within an individual WT, thus powering it up after a complete shutdown and later utilizing this powered-up turbine for restoring the other WTs. Once the whole OWF is up, the wind farm controller could be utilized to synch the OWF with the black grid, thus supporting its B.S., as shown in Figure 4d - 3.

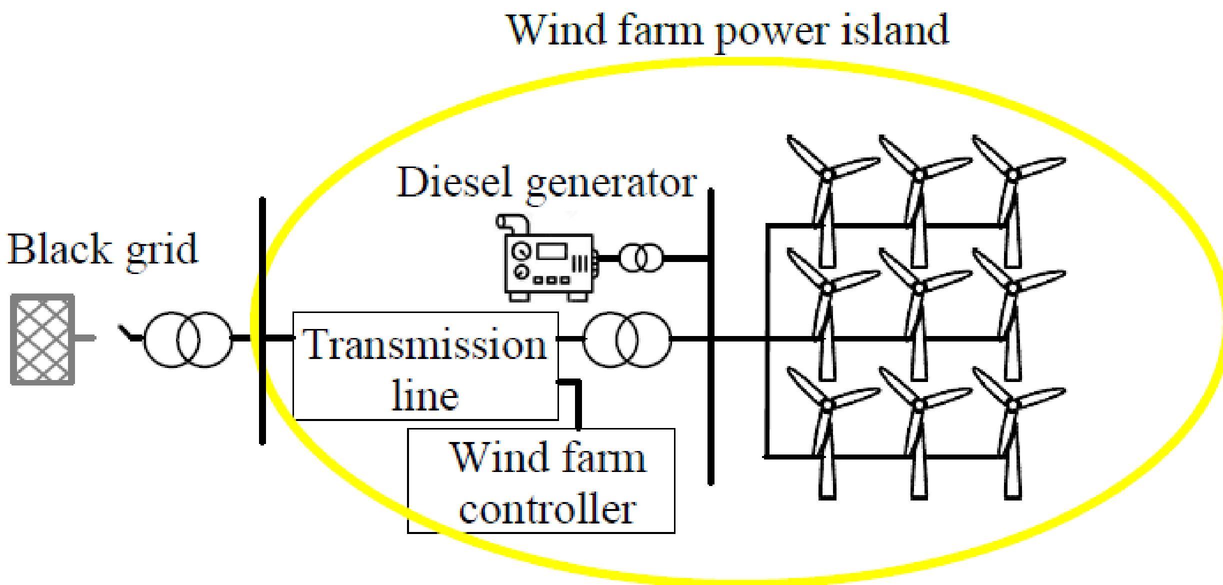

Figure 4d - 3: Black start restoration of OWFs utilizing diesel generator [7]

- *Battery energy storage system (BESS)*

A BESS integrated into the OWF, either at the offshore substation or the onshore substation, also provides a valuable resource for the self-start of OWFs, thus meeting this essential criterion for B.S. [17]. In this case, the WT converter controller should be capable of operating in the GFR mode [18]. The smaller/modular BESS can also be integrated into an individual WT, thus powering it up after a complete shutdown and later utilizing this powered-up turbine to restore the other WTs. These BESS integration strategies are shown in Figure 4d - 4.

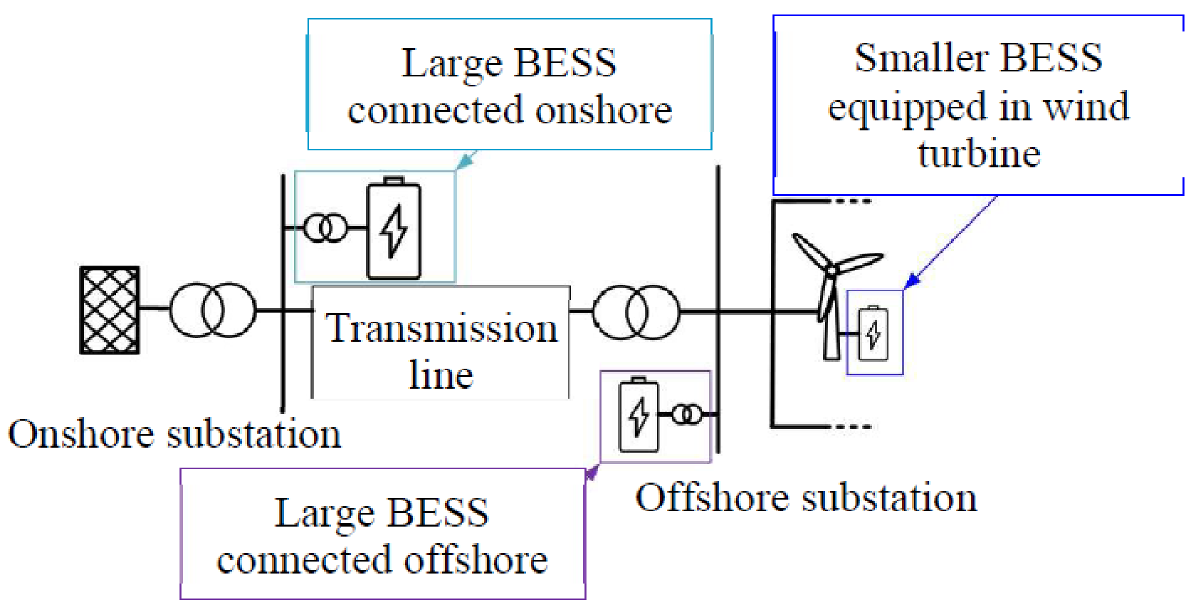

Figure 4d - 4: Black start restoration of OWFs utilizing a BESS [7]

In addition to electrochemical batteries, hydrogen electrolyzers and supercapacitors can also be utilized for the B.S. of OWFs [19]. The substation BESS provides a dual advantage; as the wind is a volatile resource and might be available in excess during periods of low grid demand and vice versa, the BESS can store excess energy during high wind conditions and provide it during low wind conditions or high grid demand [20]. This is a highly desirable feature from renewable energy resources like WFs and PV farms and could also support the B.S. procedures as discussed above.

- *Utilizing large interconnected offshore grid*

Although wind is a variable resource and might not be available at a particular OWF location when required during a B.S., a large interconnected offshore grid could be valuable to power up WTs with sufficient wind availability and later utilize these WTs to power up other WTs in the system with low wind availability. Several topologies for large offshore grids have been proposed earlier, where Figure 4d - 5 shows a backbone grid design for NewYark ISO (NYISO) and PJM Interconnection. Typically, over such a large geographical area, there is a high probability of certain OWFs always receiving enough wind to keep them running. Therefore, the running WTs act as a grid source to bring the offline WTs online in a short duration of time.

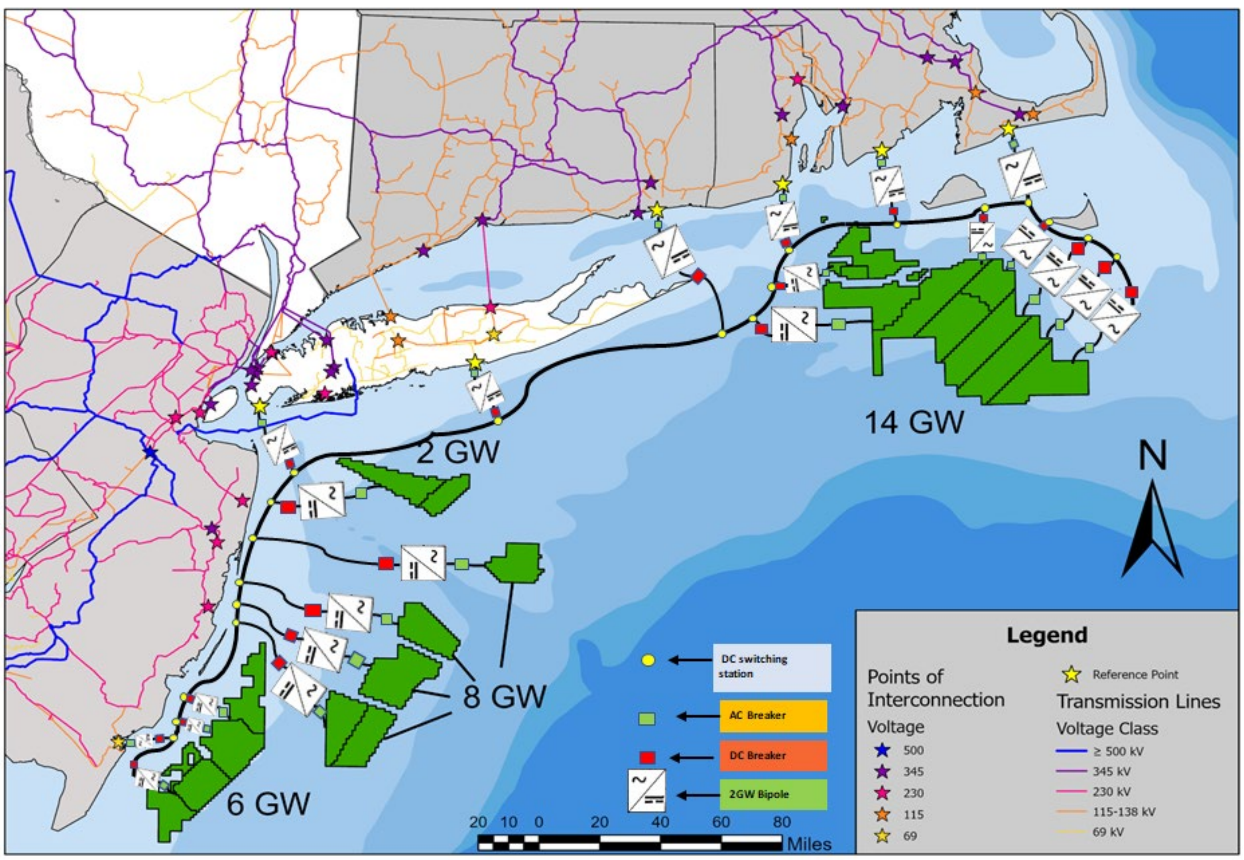

Figure 4d - 5: Earlier proposed offshore multi-terminal HVDC (MTDC) backbone grid design for New York ISO (NYISO) and PJM Interconnection [21]

4d-2.2 Duration of service availability

Another critical criterion that B.S. resources should meet is the duration of service (D.S.) availability, which defines how long a B.S. generator or source should operate independently to restore power to a grid following a complete outage. B.S. sources are typically designed to provide sufficient power and operational duration to allow for the phased restoration of other grid components, such as larger power plants, until normal operations can resume [22]. During the B.S. process, the transmission systems operators' (TSOs) requirements should be met at all costs for reliable system restoration. The typical D.S. availability level from B.S. resources is set at 90% [23].

The BESS, coupled with WFs, is an attractive way to boost the contributions OWFs can make toward the B.S. process and requirements. It is pertinent to mention that the combination of BESS and OWFs can provide up to 80% D.S. availability, which is a lower level of availability compared to the existing requirement that currently prohibits the contribution of OWFs to B.S. operations [24]. However, if this threshold is reduced to 80% by TSO, it will lead to a significant number of OWFs contributing to the B.S. operation.

The other critical issue is that the B.S. service availability is usually contracted for 40 days per year, which is challenging when considering volatile renewable energy generation such as OWFs. However, if the U.S. offshore grid is planned as a connected infrastructure, such as the backbone structure discussed above, the aggregation of multiple wind farms could reliably deliver the B.S. services for a longer period of time [25].

4d-2.3 Inertia

The other critical requirement for B.S. resources is the provision of sufficient inertia from units committed to providing B.S. services [26]. This is challenging for WTs as they are primarily pure power electronics-based resources. However, this can be handled through virtual inertia provision by these power-electronics-based resources [27]. A BESS coupled into the WT system could act as a valuable resource towards inertia provision by these volatile resources.

A comparison of inertia provision by a variety of conventional resources and WTs is shown in Table 4d – 1 [7].

Table 4d - 1. Comparison of inertia provision by a variety of conventional resources and WTs

	Synchronous generator	*BESS*	*Wind turbine*	*STATCOM*	*Synchronous condenser*
Application	Self-start, dynamic compensation, overloading capabilities	Self-start, fast dynamic compensation	Self-start, fast dynamic compensation	Fast dynamic compensation and voltage recovery during faults	Dynamic compensation and voltage recovery during faults, overloading capabilities
Availability	Dependent on fuel	Dependent of stored energy	Dependent on wind	/	/
Inertia provision	Real	Virtual	Virtual	Virtual	Real

4d-2.4 Control and Interoperability

The OFWs have WTs located far away from each other, which makes communication a challenge.

The B.S. utilizing OWFs is an intricate control procedure that requires a central controller to coordinate all the B.S. operations [28]. Communication is critical as self-starters need to communicate for step energization of the system. The central grid controller must transmit the control commands during B.S. procedures to individual WT converter controllers at a very rapid pace. Low-latency communication between the central grid controller and individual converter controllers is required, which could be ensured by utilizing advanced communication protocols, such as EtherCAT, PESnet, SyCCo, or RealSync.

The central grid controller is critical to ensure stable operation of the restoring grid under all possible scenarios by dispatching required control commands. The central grid controller is responsible for achieving the dynamic and steady-state performance of the restoring grid including:

(Dynamic performance: ~40us)

- handling of fault scenarios by utilizing fault-clearing strategies and control adjustments
- adjusting controls to handle rapid voltage and frequency fluctuations to avoid secondary blackout

(Steady-state performance: 10's of ms)

- operational management, such as adjusting the droop values of individual converters to modify the load flow
- controls to handle power generation from wind farms
- optimal power system operations

A conceptual diagram of the communication between the master controller and individual OWF HVDC converter controllers is shown in Figure 4d - 6.

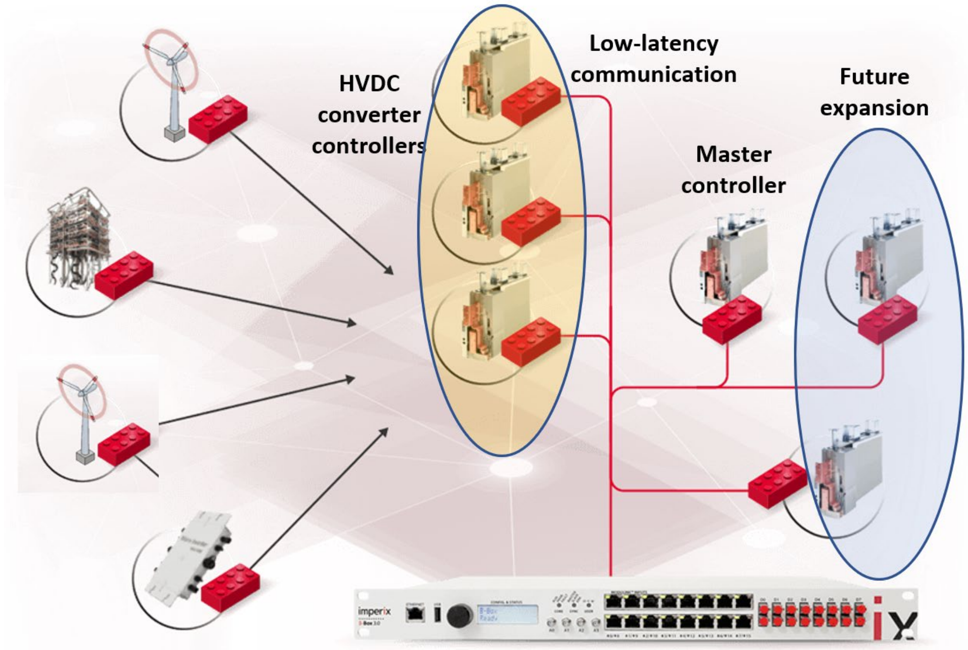

Figure 4d - 6: Communication diagram between central offshore grid controller and individual OWFs converter controllers

The converter, communication, and control equipment utilized for a large OWF network could be from different manufacturers. This brings crucial interoperability challenges that must be addressed in the design stages to avoid communication mismatches and failures [29]. To validate the interoperability of the converter controls from different vendors, the Controller Hardware-in-the-Loop (C-HIL) technique could be employed [30]. C-HIL is a real-time simulation approach where the physical controller hardware (e.g., a converter controller from a vendor) is interfaced with a real-time digital simulator (RTDS) or Hardware-in-the-Loop (HIL) system. This allows the controller's performance to be tested without requiring the actual power hardware. The real-time simulator emulates the power system in this approach, including grid dynamics, converter models, and environmental conditions. The controller operates as it would in the field, receiving real-time signals (e.g., voltage, current, frequency) and sending control commands back to the simulated system.

The following are the key features of the C-HIL approach for control validation:

1. Interoperability Testing
2. Performance Validation
3. Risk-Free Testing
4. Reduced Development Time
5. Compliance and Certification

The C-HIL concept to validate the coordination performance of multi-vendor converter controllers is shown in Figure 4d - 7.

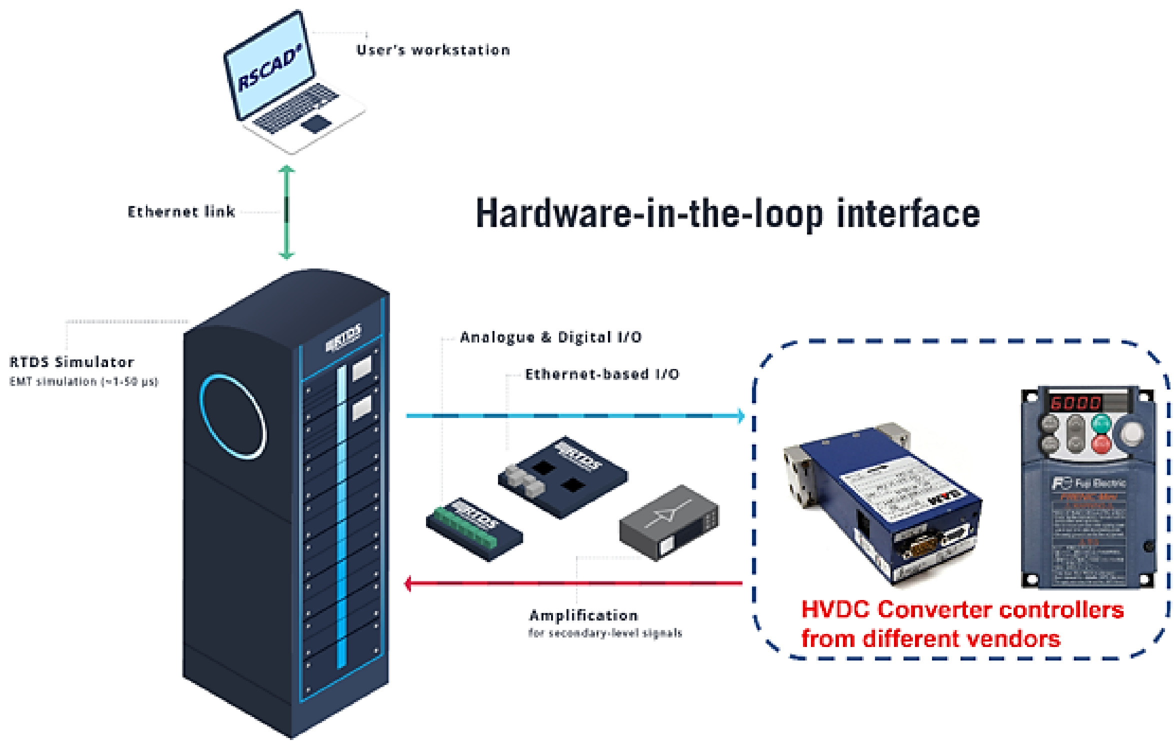

Figure 4d – 7: C-HIL setup to identify black-box model of OWF HVDC converter controllers

4d-2.5 Dynamic response

The OWFs, as B.S. units, must withstand transient phenomena due to equipment energization [31]. Owing to the existence of submarine cables, a non-negligible shunt capacitance exists in the offshore transmission system that might excite lower natural or resonant frequencies. This might lead to increased voltage levels at grid interconnection when energizing an unloaded or lightly loaded line, which can activate protective relay operations or damage the high-voltage equipment. Voltage transients might also occur due to a variety of switching operations during the B.S. However, the VSC-HVDC systems' rapid reactive power absorption/injection capability effectively counters these voltage transients [32]. The B.S. capability allows the offshore HVDC system to initiate faster power grid restoration in the event of a complete or partial shutdown. The offshore HVDC systems are typically connected to weak onshore grids (characterized by low short-circuit capacity, high impedance, and sensitivity to disturbances) and regions vulnerable to extreme weather events, such as hurricanes. Therefore, this capability is extremely helpful in a system shutdown, thus restoring power to critical loads with minimal interruption.

This capability allows renewable energy to play an active role in grid recovery. In essence, B.S. capabilities allow for greater energy solutions and help avoid using traditional B.S. sources, including power plants that aren't environmentally friendly.

4d-2.5 Harmonics

Another critical issue during B.S. is the resonance that may occur during the energization procedure due to different power converters switching operations and their interaction with cables, transformers, and other passive elements. During the black start, the overall damping of the system is low due to the lack of synchronous generators (which naturally absorb harmonics).

The resonance during B.S. may lead to the following issues:

1. Overvoltage
2. Instability
3. Reduced Restoration Speed
4. Equipment Damage
5. Operational Uncertainty

This issue can be addressed by utilizing passive filters (tuned or broadband filters) and active harmonic filters (AHF) that change their filtering abilities per system topology and system loads, or by using advanced converter control strategies [33].

INDUSTRY INSIGHT

The National HVDC center leads the improvement of Great Britain's Black Start capabilities using HVDC [34]. The HVDC Centre technical experts, in collaboration with specialists from SHE Transmission, Scottish Power, National Grid and the Scottish Government, carried out an in-depth study which included:

- Review of existing Black Start arrangements in GB alongside analysis of how HVDC schemes perform against Black Start technical requirements;
- Evaluation of global HVDC Black Start experience and examination of global black-out events;
- Mapping these findings against GB's current and future HVDC schemes (with a focus on Scotland and the North of England) to identify practical opportunities; and
- Developing specific recommendations, in consultation with Stakeholders, to maximise the use of HVDC schemes for improving GB's Black Start arrangements
- The center provided seven key recommendations:

Opportunity	Recommendation
There is little guidance for HVDC Schemes on what Black Start services should be specified.	Define (and promote) the Black Start services that should be specified in all future schemes.
Black Start is a highly unusual situation, with a high risk of AC network protection, or the HVDC system protection trip during energisation.	Develop protection testing capabilities for both the AC system and HVDC system (as a combined system), for restoration scenarios.
During re-energisation; energised 'islands' need to be connected (and re-synchronised), requiring complex control and data exchange.	System studies are required to ensure the HVDC controllers transition as required during re-synchronisation other power islands.
The limited testing of HVDC Black Start functionality does not give the required level of confidence that it would act as expected on the real network.	Perform combined factory testing, real-time demonstration, control room operator training and field trials to build confidence in the robustness of Black Start operation.
The Black Start services that HVDC schemes provide could be significantly enhanced if combined with synchronous compensators and other additional devices.	Investigate the potential enhancing the Black-Start services by combining HVDC Converters with synchronous compensation devices and other additional equipment.
Some of the criteria regarding the provision of Black Start services are not appropriate for HVDC schemes.	Review the Black Start service criteria to ensure that HVDC schemes are not unnecessarily dis-qualified.
There are additional HVDC Black Start enhancements that merit further investigation.	Investigate further: o Using offshore windfarms (or island generation) to help energise the network, and o Reducing system voltage during restoration to speed-up the time-to-restore.

The above section has discussed in detail the different requirements for B.S. operations and the associated challenges the OWF resources can meet when planned to be utilized as a B.S. resource. This section also discussed possible solutions that could be adopted for the successful operation of OWFs as B.S. resource.

4d-3 Differentiating grid forming controllers (GFM) from traditional grid following controllers (GFL)

Common WTs do not include the self-start capability as they are grid-following (GFL). Therefore, it is essential to implement a self-start unit that could be a diesel or biomass-powered synchronous generator or power-electronics-based GFM unit.

The GFM control capability, when introduced in HVDC converters, allows them to operate as a voltage source that sets the frequency and voltage of the network to emulate the behavior of synchronous generators with no external grid [35]. The GFR converters utilize an oscillator-based control loop to create a grid reference frequency in the absence of an existing grid. Further, a droop control is implemented for frequency stabilization under varying load conditions. Similarly, control loops are also utilized to regulate the terminal voltage. The GFR feature allows WTs to initialize and re-energize the grid during a B.S. scenario. It also helps provide grid or synthetic inertia, improving frequency and voltage stability.

The GFR converter controls fundamentally differ from GFL converters, which synchronize to an existing grid utilizing a phase-locked loop (PLL) [36]. The GFL converters can't work without grid reference voltage. Therefore, a stable grid frequency and voltage are required for synchronization. The GFL converters act as a controlled current source and maintain the constant DC link voltage to deliver all the power generated by OWFs to the grid while maintaining a constant voltage at the PCC. In essence, the GFM converters work as ideal AC voltage sources with low output impedance, whereas the GFL converters act as current sources with high parallel output impedance.

The key differences between the GFL and GFR controllers are highlighted in Table 4d-2.

Table 4d - 2. Highlights of the major differences between GFL and GFR

Feature	GFL Controller	GFR Controller
Operation	Follows grid voltage and frequency	Forms grid voltage and frequency
Inertia Contribution	Does not provide inertia	Provides synthetic or real inertia (with energy storage)
Independence	Requires a stable grid to operate	Operates independently (islanded mode)
Use in Black Start	Not suitable for black start	Suitable for black start
Control	Current source	Voltage source
Applications	Grid-tied solar, wind, and DERs	Microgrids, high-renewable systems

There are several key considerations in the design of a GFM controller for the B.S. capability of HVDC systems. The controller should be capable of:

a) Independently controlling both voltage and frequency

b) The controller should emulate the inertia typically provided by rotating machines in conventional power systems

c) Fault tide through (FRT) capability to detect faults and maintain stable operation by implementing current limiting and voltage support functions

d) For multi-terminal HVDC (MTDC) systems, the GFM controllers should ensure the proper sharing of active and reactive power among terminals

e) The MTDC stations need to actively route power between terminal stations

The VSC-HVDC systems, unlike line-commutated converter (LCC) based HVDC, possess inherent B.S. capabilities. During the VSC-HVDC systems-based B.S., the converter on the OWF side controls the DC voltage of the HVDC cable. The converter on the blackout grid side converts the DC voltage into fully controllable AC voltage. This allows the full OWF converter active and reactive power capability to support the AC grid.

INDUSTRY INSIGHT

A CIGRE Working Group B4.102, titled "Technical Requirements and Scenario Considerations on Grid-forming Capabilities of VSC-HVDC Systems," has been formed that focuses on defining the technical and regulatory frameworks necessary for Voltage Source Converter High Voltage Direct Current (VSC-HVDC) systems to effectively support and stabilize modern power grids through grid-forming (GFM) capabilities [37]. This group has been formed to establish mandatory and optional GFM requirements for VSC-HVDC systems to ensure compliance with grid codes and improve grid stability. It also covers the seamless transition between the GFM and GFL control modes for the VSC-HVDC substations.

cigre

CIGRE Study Committee B4

PROPOSAL FOR THE CREATION OF A NEW WORKING GROUP

WG[1] B4.102	**Name of Convenor:** Zhiyong Yuan (CHINA) **E-mail address**: yuanzy1@csg.cn	
Strategic Directions #[2]: 1		**Sustainable Development Goal #[3]: 7, 9, 13**
This Working Group addresses these Energy Transition topics:		
☐ **Storage** ☐ **Hydrogen** ☐ **Digitalization** ☐ **Sustainability and Climate Change** x **Grids and Flexibility** x **Solar PV and Wind** ☐ **Consumers, Prosumers and Electrical Vehicles** ☐ **Sector Integration**		☐ **None of them**
Potential Benefit of WG work #[4] : 1, 2, 3, 4		
Title of the Group: Technical Requirements and Scenario Considerations on Grid-Forming Capabilities of VSC-HVDC Systems		

The GFM capability is crucial for B.S. operations where the offshore grid must be restored without relying on external power sources/onshore grid. To maintain voltage and frequency stability during the B.S. restoration via offshore HVDC systems, careful planning is essential for sequential load restoration to avoid system overloading. As the converters feed the AC grid during the B.S. procedure, the AC-side protection settings need to be adjusted to allow for correct tripping during an AC fault when limited current is supplied by the converters. This requires extensive modeling, simulation and HIL testing to validate B.S. capabilities of HVDC systems.

4d-4 Grid-forming controller design followed by a black start restoration strategy for offshore HVDC systems

The state-of-the-art wind turbines are constantly being upgraded to provide services such as low-voltage-ride-through (LVRT) and fast frequency response (FFR), inertia emulation, reactive current injection, and power oscillation damping. However, the prevalent GFL WTs, instead of acting as B.S. units, could contribute to the recurrence of blackouts after a grid collapse event, as the grid is not stable enough at the start of the restoration process, and GFL devices require a strong grid for their optimal operation [38]. The GFM control of renewables for microgrid applications has already been widely studied at the distribution level. However, sufficient information is not available for GFM control at high power levels.

One way to utilize existing GFL WTs as B.S. resource is to integrate them with an external power supply, such as a diesel generator (DG) or energy storage (ESS) coupled with a STATic synchronous COMpensator (STATCOM), where the power supply provides a voltage, frequency (V, f) reference to the GFL WTs and the STATCOM meets the VAR requirements of the cables and transformers to stabilize the voltage [39]. Once the WT is up, it is capable of supporting the rest of the grid in power restoration. However, it is faced with challenges such as high inrush currents, transient overvoltages, and loss of synchronism and resonance that could jeopardize the B.S. process [40]. The restoration process using GFM control involves the energization of the offshore AC network, including transformers, cables, and converters, followed by HVDC link energization and onshore converter pre-charging and deblocking to pick up the block load. GFM allows PEC to mimic synchronous generators, allowing droop-based load sharing, synthetic inertia emulation (helps to avoid V, f variations during the B.S. process), synchronized and stand-alone operation, and B.S. behavior.

The design of a GFM controller for an offshore HVDC converter with B.S. capability is a complex task that requires careful consideration of several technical aspects. GFM controllers enable HVDC converters to establish and maintain stable grid voltage and frequency, which is essential for B.S. operations. Here's a detailed overview of the design considerations and steps involved.

4d-4-1 GFM design considerations

1. The GFM controller must be capable of <u>independently controlling both voltage and frequency</u>. This is crucial for B.S. operations, where the grid is initially de-energized. Moreover, the controller should emulate the inertia typically provided by rotating machines in conventional power systems to stabilize the system.

2. The <u>VSC-HVDC technology is generally preferred</u> for offshore HVDC applications due to its superior control capabilities, including B.S.

3. The controller must include mechanisms to dampen oscillations and maintain system stability during the transition from B.S. to normal operation. Moreover, proper filtering techniques should be implemented to <u>mitigate harmonics</u> generated by the converter.

4. <u>Reliable and fast communication</u> links between the offshore HVDC converter and the onshore grid are essential for effective B.S. and overall operation. Also, the offshore controller must coordinate with onshore protection and control systems to ensure a <u>smooth synchronization</u> process.

4d-4-2 GFM Design Steps

1. The OWF controller <u>design should be adaptive</u>, i.e., it should be capable of establishing a stable reference for both voltage and frequency based on a predefined setpoint during the B.S. operations. During normal operations, the controller should switch to its typical GFL mode, which involves the utilization of a Phase-Locked Loop (PLL) to synchronize with the grid.

2. The controller should <u>emulate the inertia of conventional generators</u> that provide the OWF the capability to handle dynamic events in grid startup during a B.S. procedure. This involves the implementation of a Virtual Synchronous Machine (VSM) control. The VSM mimics the behavior of a synchronous generator by dynamically adjusting the output voltage and frequency in response to power imbalances.

3. The controller should also be capable of maintaining active (P) and reactive (Q) power balance. This could be achieved by using a droop control strategy for P and Q power. This involves adjusting the output frequency in response to active power changes and the output voltage in response to reactive power changes.

4. The B.S. controller should ensure system stability during and after the B.S. process. This can be achieved by implementing power system stabilizer (PSS) functions and the use of advanced control techniques like proportional-resonant (PR) controllers to dampen oscillations.

5. To minimize harmonics in the system, active and passive filtering techniques can be incorporated within the controller design to reduce harmonic distortion.

The GFM control block diagram is shown in Figure 4d – 8 [37]. The GFM converters work in a closed loop and consist of different control blocks in dq reference frame, as shown in the figure. This converter acts as an ideal AC voltage source with amplitude v* and the angular frequency ω* that the converters provides at the PCC. This is done utilizing a voltage control loop where the error between the measured voltage v_{abc} and the reference voltage v* is minimized. To avoid over currents during transients, an inner current control loop is added in series with the voltage control loop, where the former has a smaller time constant than the latter for decoupling the control loops. The control action is performed in a synchronous reference frame (SRF) that requires an angle theta (θ) that is obtained through the integration of the angular frequency setpoint. The final computed reference signal u_{abc} is provided to the PWM block to control the converter switches. The converter output is equipped with an LC filter comprising an inductor L_f and a capacitor C_f to extract the harmonics before feeding the grid.

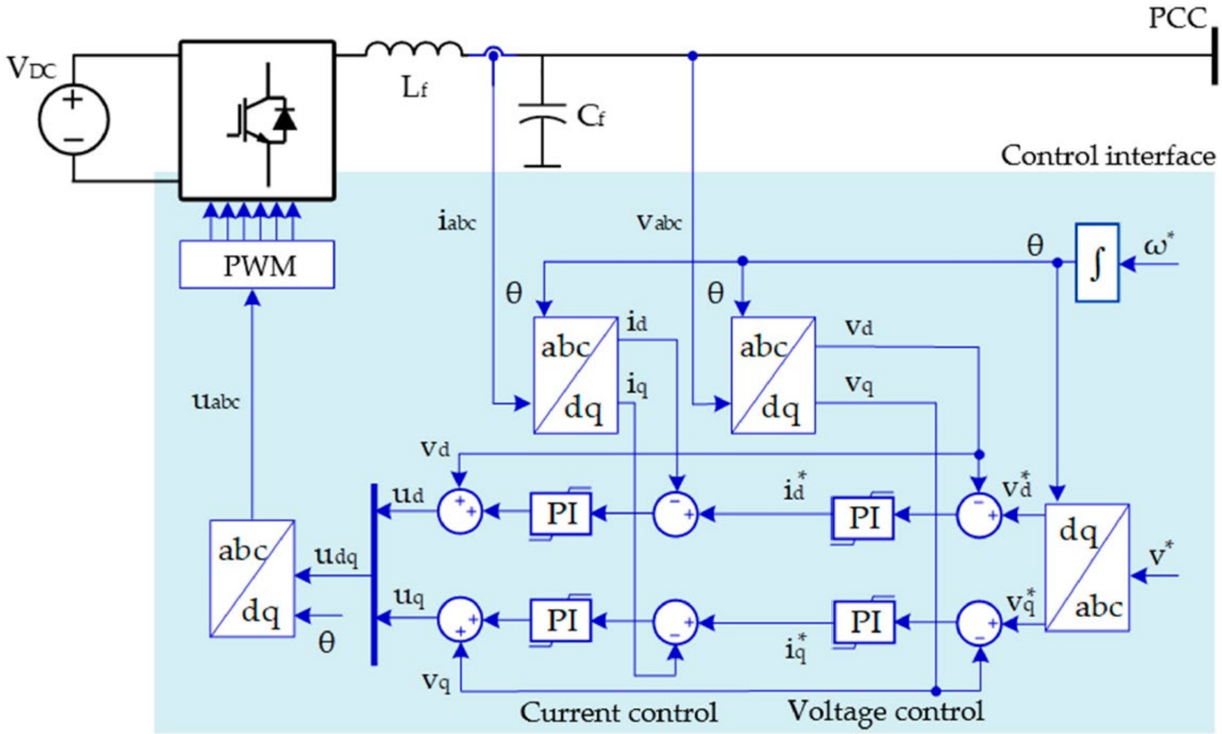

Figure 4d – 8: GFM controller block diagram [37]

The most common and simplest strategy to control the active P and reactive power Q shared with the grid is the droop control-based GFM control, which is depicted in Figure 4d – 9 [37].

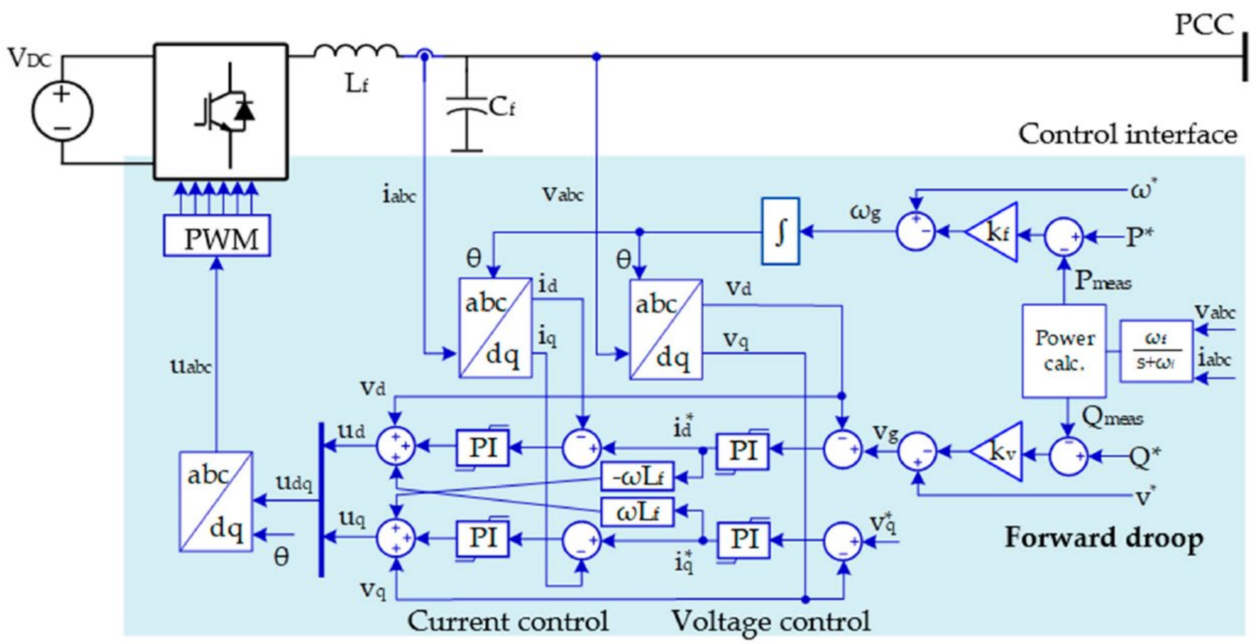

Figure 4d – 9: GFM droop controller block diagram [37]

Droop control primarily mimics the regulation characteristics of synchronous generators (SGs). Droop control has emerged as preferred approach over the centralized controllers and master-slave configuration as they don't require any communication with the rest of the system to control their operation which is helpful during conditions such as B.S. The basic governing equations for the droop control are shown below:

$$v_g = (Q^* - Q_{meas})k_v + v^*$$

$$\omega_g = (P^* - P_{meas})k_f + \omega^*$$

Where,

k_v: voltage droop coefficient
k_f: frequency droop coefficient
v_g: actual grid voltage
ω_g: actual grid angular frequency
v^*: reference grid voltage
ω^*: reference grid angular frequency
P^*: reference active power
Q^*: reference reactive power
P_{meas}: measured active power
Q_{meas}: measured reactive power

The droop-based control scheme is highly reliable and flexible, as discussed above, but has its inherent disadvantages, such as load-dependent frequency deviation, slow dynamic response due to filters for power measurement, and non-linear load-sharing issues resulting from harmonics. To resolve these challenges, a variable virtual impedance at the output of the converter can be utilized to add harmonic droop characteristics with additional damping and the improved trade-off between current harmonic sharing and voltage total harmonic distortion (THD) by adjusting output impedance seen at different frequencies.

Several advanced GFM strategies have been proposed to replicate the behavior of synchronous generators, including inertia and damping, f, V droop, self-organizing parallel operation and automatic power sharing [39]. These include:

1. Virtual synchronous generator (VSG)
2. Power synchronization control (PSC)
3. Distributed PLL-based (dPLL) control
4. Direct power control (DPC)

A comparison of different GFM control strategies is presented in Table 4d – 3.

Table 4d - 3. Comparison of different GFM control strategies

GFM control strategy	Advantage	Disadvantage
Droop based	Automatic power sharing	May lead to steady-state errors
VSG based	Explicit inertia emulation	Numerical instability
PSC based	Particularly designed for weak grid cases	May lead to steady-state errors
dPLL based	Plug-and-play capability	Little research on it
DPC based	Able to work in weak grids	Complex

4d-4-3 Black Start Restoration Strategy

Following is the restoration strategy for safely and efficiently energizing the grid from an offshore HVDC source [5]:

1) Initialize the OWF HVDC converter with GFR mode. The HVDC system starts with an energy source like batteries or local generation. The GFR controller regulates voltage and frequency autonomously.
2) The next step is the gradual connection of wind turbines to provide additional power generation. The control strategy ensures multiple WTs synchronization without causing instability.
3) After that, the gradual energization of the offshore HVDC substation is performed.
4) Once the HVDC substation is energized, sequential energization of passive components, such as HVDC transmission lines and onshore substations, is performed. This is achieved through sequential energization of the array cables and WT transformers, starting with one WT energizing its string, moving to the next, and sharing the control of V, f. This allows shorter links to be energized first, followed by the longer ones.
5) After that, stepwise restoration of loads in blocks is performed to prevent overloading or voltage collapse.
6) This overall procedure discussed above is performed by several OWF groups in parallel which are later synced to restore the overall power grid.
7) Once the B.S. process is complete, the OWF HVDC returns to its normal GFL mode.

4d-4-4 Implementation and Testing

Implementing B.S. capability in OWFs is a complex task and requires robust testing before field deployment. Following are the suggestions for the evaluation of the B.S. control before its field deployment.

1. The first step is detailed modeling and simulation of the offshore HVDC system and GFR controller. This involves the use of simulation tools like PSCAD, or DIgSILENT PowerFactory to test the controller under various scenarios, including B.S. conditions.

2. Once the steady-state and dynamic performance of the control scheme is verified, controller hardware in the loop (C-HIL) testing should be performed to validate the controller's performance in real-time. HIL setups allow testing the controller with actual hardware components, providing a more realistic assessment of its behavior.

3. The next step would be to implement the controller in a pilot project to test its performance in a real-world environment. Later the pilot project should be gradually scaled up to full deployment, incorporating lessons learned from initial trials.

Following the above steps ensures the OWFs fully act as an effective and resilient B.S. resource.

4d-5 Energy equity issues related to Blackstart services provision through Offshore Wind Farms

This section will address the energy equity issues that arise as a result of shifting the B.S. services provision from conventional fossil-fuel-based power plants to OWFs. Module 12a further addresses the effects of HVDC on energy equity and environmental justice.

Lack of access to reliable power: As discussed earlier, B.S. services are critical for restoring power after a grid blackout. Primarily, vulnerable communities without access to the main power grid or a strong grid solely rely on these renewable resources for grid restoration after a blackout. They may experience longer restoration times when compared with communities in proximity to fossil fuel-based power plants that have a well-established B.S. process, which is the result of weak regulations and ineffective B.S. services integration into OWFs.

Cost allocation: Integrating B.S. services into OWFs requires a significant expense for developing GFM inverters, deploying energy storage systems, and developing grid control. When these costs are passed down to ratepayers, it affects low-income households more as they are already faced with energy affordability issues.

Technical and policy barriers: Conventionally, the B.S. services are provided by traditional sources of energy, and therefore, the B.S. regulations are centered around these resources, such as gas, hydro, and nuclear power plants. This is a significant policy barrier towards including OWFs into B.S. services provision. These barriers significantly affect communities that solely rely on renewable resources that are primarily disadvantaged communities. Incentivizing renewable-based B.S. and directing investments toward resolving their associated technical challenges could be critical to benefiting disadvantaged communities from these resources.

Geographic disparities: As the OWF's resources are located in close proximity to wealthier coastal areas, the B.S. services from these resources have minimal impact on the underprivileged communities living inland. The transmission system must be upgraded to include HVDC energy corridors that could transfer the benefits of OWF energy resources toward communities living further away from the shore. The federal/state funding should be directed towards ensuring B.S. services benefit the disadvantaged communities.

Job equity consideration: All the OWF's development and integration of B.S. services provide a significant workforce and economic development opportunity. This development must be inclusive, including underrepresented communities, to avoid inequalities and transfer the maximum benefits from the OWF resource to vulnerable communities.

4d-6 Summary of Main Learning Points

A successful B.S. after a grid blackout is highly critical to reduce grid downtime and enhance the resiliency of the power systems against extreme events. The VSC-HVDC-based OWFs have the capability to restore and stabilize a blackout grid through proper control and restoration strategy. As the restoration time decreases exponentially with the availability of B.S. units, these additional B.S. resources must be effectively utilized to assist in grid restoration after a blackout. It is pertinent to mention that not all WTs need to be equipped with GFM controllers for an effective B.S. Only 25% of WTs equipped with these controllers could be sufficient to bring the whole OWF up and support the grid initialization after a grid blackout. The synchronization of the WTs is critical, which could be achieved by using a few GFM units and the rest as GFL units.

Although a large group of WTs located at different geographical locations and connected via a common line could self-start and help power up other downed WTs, the BESS and WT combination could provide a more resilient B.S. source. The BESS has a negligible cost as compared to the services it could offer to the WT and overall grid industry. The BESS can be placed both onshore and offshore. However, there are several benefits associated with installing the BESS onshore. First, its size could be increased, and maintenance could be easily performed when it's situated onshore.

Simulations and HIL demonstrations would be critical for proof of concept of B.S. through OWFs before field implementations. Denmark and Ireland have already been utilizing their VSC-HVDC Norway and Great Britain interconnection (North-Sea Link) for B.S. servicing. The Skagerrak-4 VSC-HVDC link that exists between Norway and Denmark has already been demonstrated to energize the voltage of an islanded 400/150 kV Denmark network to energize overhead transmission lines, transformers and block load, which was followed by synchronization with the EU. In addition, a top-down restoration test of the NEMO link between the UK and Belgium has also been demonstrated to energize a dead Belgian grid utilizing the VSC-HVDC interconnector and live UK side grid.

Organizations such as IEEE and CIGRE provide detailed guidelines, technical brochures, and case studies regarding GFR control of converters. The CIGRE working group WG B4.102 is already working on the technical requirements and scenario considerations on GFR capabilities of VSC-HVDC based systems [41]. These documents must be consulted for best practices and real-world applications. Also, white papers from industrial manufacturers like ABB, Siemens and GE provide detailed information on the design, testing and deployment of such systems. Through proper control, coordination and planning, the OWFs could play a pivotal role in grid restoration after a complete/partial blackout.

Problems

Problem 1: What is the role of OWFs HVDC converter stations in B.S. services provision?
Solution: As discussed in section 4d-1, the OWF HVDC converters transfer power generated from offshore wind turbines to the onshore grid. These converters, when operated in GFM mode for independent voltage and frequency development, could provide B.S. services to the main grid by restoring its various sections, provided enough energy storage or wind is available.

Problem 2: What are the key design considerations for a GFM HVDC converter utilized for B.S. services provision?
Solution: As discussed in section 4d-4-1, the following are the key design considerations:

a) Independent V, f generation without an external grid
b) Emulate synthetic inertia for grid stabilization during restoration
c) Adaptive transformation from GFM mode to GFL mode
d) Robust communication/coordination between different OWF blocks

Problem 3: Can you explain the difference between a GFL controller and a GFR controller?
Solution: As discussed in section 4d-3, the GFR controller actively regulates the voltage and frequency independent of the main power grid. On the other hand, the GFL controller requires an external grid reference and therefore, the GFL controller cannot initiate a B.S. on its own.

Problem 4: What are the different GFM control strategies that can be used for HVDC converters for blackstart?
Solution:

a) Droop control that allows an HVDC converter to operate autonomously and work together with other HVDC converters to maintain the voltage, and frequency of the restoring grid.
b) Virtual synchronous generator (VSG) control that allows the HVDC converter to act as a synchronous generator by providing virtual inertia, frequency regulation, and damping, helping the HVDC converter to support grid restoration after a blackout.
c) Distributed PLL-based (dPLL) control, in contrast to GFL converters, allows the GFM converters to form their own voltage and frequency reference without requiring an external grid signal. The dPLL uses voltage and current feedback from the converter to adjust its phase/frequency, which helps to match the converter output voltage with the system voltage.
d) Direct power control (DPC) controls the active and reactive power injected into the grid and regulates the grid voltage and frequency with no existing grid reference.

Problem 5: What are the regulatory and standardization challenges facing HVDC-based blackstart implementation?
Solution:

a) Grid code compliance issues, as current standards are designed for conventional generation
b) Testing and certification capabilities to evaluate the B.S. capability of GFM converters are still evolving
c) Interoperability issues as different manufacturers' HVDC-based systems are involved in OWF developments, and they must be coordinated for a planned restoration.

Problem 6: Perform abc to dq0 transformation for a set of balanced positive sequence (ABC) three-phase voltages at θ=0.

Solution:

As the set of three-phase voltages is balanced in the positive sequence:

$$v_a = \sin\,(\omega t)$$

$$v_b = \sin\,(\omega t - 120)$$

$$v_c = \sin\,(\omega t + 120)$$

Applying the Park transform, we get the transformation matrix,

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

Put $\theta = 0$,

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} = \begin{bmatrix} 0 \\ \frac{-\sqrt{3}}{2} \\ \frac{\sqrt{3}}{2} \end{bmatrix}$$

This gives $v_d = 0$, $v_q = -1$, $v_0 = 0$

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