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Published in:
Proceedings of 17th wind Integration workshop

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Control Solutions for Blackstart Capability and Islanding Operation of Offshore Wind Power Plants

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***Abstract*— Environmental sustainability concerns make renewable energy systems (RES) integrated into the grid crucial for future power systems. Amongst RES, wind energy especially offshore wind power plants (OWPP) show huge promise. Increasing penetration of RES requires re-thinking of critical operation states that could lead to an increased risk of generation tripping that ultimately triggers blackouts. Thus maintaining reliability, robustness and stability of grid operation has become more complex and so blackstart (BS) and islanded (Is) operation requirements are being considered as options for WPPs in the grid codes. Additionally, advanced control functionalities provided by modern wind turbines (WT) owing to their power electronics converter (PEC) interface, enables them to provide fast, high power environment-friendly BS capability that facilitates grid recovery & reduces the impact of a blackout. In this paper, the motivation for BS capabilities in OWPPs has been presented, and the different stages of restoration using OWPPs identified. Finally the existing control solutions and potential challenges for BS&Is using OWPPs have also been investigated.**

I. Introduction

The rising demand for power necessitates an increase in the installed generation capacity. Moreover, sensitive and critical loads impose a need for higher reliability in grid operation. Thus environmental problems like global warming, sustainability concerns and energy security make renewable energy systems (RES) crucial for future power systems.

The European Union's (EU) 2009 directive on the promotion of the use of energy from renewable sources sets an overall goal across the EU for a 20% share of RES in the total energy consumption by 2020 [1]. The European Commission has now proposed a target of at least 27% renewables in the final energy consumption in the EU by 2030 to make the EU a global leader in renewable energy [2]. Along with the EU, other international players such as USA, China and India, are also setting out several energy strategies for a more secure, sustainable and low-carbon economy.

Amongst RES, wind energy is the fastest growing [3] due to its abundance and cleanliness [4], and shows huge promise for the future as the EU has decided to make wind power a major electricity source. In addition to quick growth in the total installed capacity, the size of the individual wind turbine (WT) is also increasing to achieve a lesser price per kilowatt hour [3]. Moreover, due to onshore space constraints, large offshore wind power plants with high power WTs have gained popularity and this has led to an increase in the share of offshore wind energy [4], [5].

This work is part of the InnoDC project that has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 765585.

However, with increasing RES replacing conventional power plants, maintaining reliability, robustness and stability of grid operation, has become more complex due to the introduction of new, variable and more unpredictable power flows [6]–[8]. Morevoer, inertial decoupling of the rotating WT generator from the grid by the power-electronics converter (PEC) interface combined with the unpredictable line overloads caused by erroneous scheduling due to larger errors in forecasting over timescale of hours, leads to violent frequency-swings and over-burdened reserves, resulting in decreased transient stability [9]. All of the above factors can result in cascaded tripping of generation and potentially trigger blackouts, especially if a large generation is involved and thus future power systems operating with a large volume of RES might require black-start (BS) capabilities and controlled islanded operation (CIO) to support the transmission system operator (TSO) in the event of a blackout to restore the power system [3], [6], [9]–[11].

The next section of this paper presents the main factors motivating the need for development of blackstart and islanding (BS&Is) capabilities in offshore wind power plants (OWPPs).

II. Motivation

The recent increase in the integration of RES like large OWPPs far from load-centres, has increased the trans-national power exchanges and led to the system being operated closer to its limits due to constraints on expansion of transmission-assets [8]. Moreveor the shift towards PEC-interfaced controllable RES is causing the system dynamics to change which poses a risk to the power system dynamic stability [8], [9]. Furthermore, the stronger linking of the national power systems, in combination with the previous factors, has translated into an increased risk of wide area blackouts [8]. Thus, with the growing proportion of wind power in the grid, more advanced grid requirements like BS, usually targeted to large thermal power plants, can be addressed by the large OWPPs that are integrated through voltage source converter (VSC) based high voltage direct current (HVDC) transmission [3]. Additionally, due to absence of near-shore wake effects, large OWPPs with cable distances of 100 km or more have steadier wind conditions compared to onshore/near-shore OWPPs that typically have higher availability uncertainty.

During the power system restoration process after a blackout, plants with black-start units (BSU), usually pump-storage hydro power plants or small gas turbines, energize a network island and generate initial voltage for supplying auxiliary power to start larger conventional thermal power plants [12]. However, this is characterized by long start-up times. In contrast, large VSC-HVDC connected OWPPs, far from the shore and composed of state-of-the-art WTs, can provide fast & fully-controlled [4], [6], [7], high-power environment-friendly BS capability with high availability [3], [12], [13]. Thus BS&Is operation requirements have been included as options for WPPs in the ENTSO-E network codes, where the relevant TSO is allowed to request these functions to support grid-recovery [4], [13].

The strategies for optimal power system restoration plans after a complete blackout are highly dependent on the location and characteristics of BSUs in the power grid such as survival & startup power, capacity, prime-mover's frequency response etc., and also the network topology of the grid under consideration [14], [15]. Since the restoration duration reduces exponentially with the availability of initial sources of power (BSUs) [16], having BS capability in OWPPs could significantly reduce the extent, intensity & duration, and thus the overall impact [16] of blackout events. Wind power integrated in the system has already been shown to improve the restoration time and reduce the unserved load energy during the restoration period [17].

Traditionally, during restoration after a blackout, the main onshore-grid is used to power the OWPP via the VSC-HVDC link in which the offshore-VSC, shown in Fig. 1, is controlled in *grid forming* [18] mode and the WTs connect as *grid following* [18] units [17]. Most WTs normally start automatically about 10 minutes after getting a stable voltage following a blackout, which encourages the TSO to include them earlier in the restoration process to participate in charging the HVDC-link and contributing in a faster load pick-up by fast ramp-up [17]. However, at the beginning of the BS-restoration process, the network is not completed and the grid is not strong enough to allow large OWPP restoration as that may lead to a second blackout [17]. Thus, OWPPs equipped with *grid forming* capabilities will not only not have to wait for completion of the network reconstruction, but can also do *controlled islanded operation* to ensure the continuity of power supply [11] and participate in sectionalizing strategy [19] for defense against blackout. This facilitates *bottom-up* grid-recovery (build-up or parallel power system restoration) that reduces restoration time & the unserved load compared to a *top-down* (build-down) approach [19], [20].

Additionally, frequency and voltage support functionalities of VSCs such as dynamic reactive power control for improved voltage stability, inertia emulation, self-commutation, indefinite operation at very-low power transfers, under-voltage ride-through etc. [21] can also be provided by the modern WT's state-of-art PEC-interface [3], [6], [9], [12], enabling them to be controlled as *offshore grid-forming* units. Self-starting WTs that can produce power to sustain themselves, can avoid the risk to their health (moisture damage, icing up of electronics & equipment, bearing deformation and vibrations due to unfavourable yaw-axis orientation) as long as there is wind, especially when off-line for long durations due to a transmission line outage or a regional black-out and thus minimize or totally avoid the use of the backup diesel generator [13]. BS-capable OWPPs also help minimize the use of the offshore-substation diesel generator backup-power for supplying the auxiliaries (controls, switchgear, climate units for VSC maintenance, station start-up) & forming the collector-grid [13]. Since presence of diesel generator increases the insurance & maintenance cost considerably, BS&Is capabilties in WTs would be a preferable economic solution.

Moreover, *offshore grid forming* WTs allow diode rectifier unit (DRU) [22]–[24] or thyristor-based line commutated converter (LCC) with reduced filter size [25], that are preferred at higher power levels, to be used in place of the offshore-VSC although it allows more controllability & flexibility. This reduces installation & operational costs, and increases efficiency, system reliability and robustness [22]–[24].

III. Control Solution

This section begins with a brief description of the target states and the major/significant technical challenges in the proposed OWPP BS-energization sequence followed by the control strategies required for BS&Is capabilities in OWPPs.

A. Target States

For complete power system restoration, three stages must be completed viz. the *restoration* of generation units, the transmission system, and the loads with the aim to minimize restoration time & maximize load picked-up at each moment [17]. After the *decision* to implement BS-plan is taken, a set of *defensive* actions are carried out to save as many generation units as possible followed by a clearly defined plan with the *target system-states* and the steps to achieve them, to avoid re-blackout. These mainly inlcude the *blackstart* of BSUs, *voltage propagation* to crank-up non-BSUs (with islanding), *energization* of the bulk power transmission system, optimal *load pick-up* while maintaining system stability, and finally, *meshing* & *island synchronization* to enhance the resilience of the recovered network against contingencies, before connecting to the grid [11], [14], [16], [19].

Taking inspiration from the grid-restoration procedure as described above, the OWPP-BS energization sequence can be separated into *target states* [21] presented below with a schematic explanation in Fig. 1.

1) Self-Start: The first step is the *self-startup* of the WT using an internal backup power supply for initial energization of its auxiliaries and yaw & pitch mechanisms, to start producing power from the wind, without depending on an external power supply [13].

2) Self-Sustain: Once the rotor is oriented to the wind direction, the WT can start rotating and producing energy to sustain itself, assuming steady high wind conditions. This requires the WT grid-side converter (GSC) to operate in a *power-curtailed* [13] *grid-forming* [18] mode for energizing the WT-transformer and supplying the auxiliaries & controls.

3) Parallel Operation: Once WTs can sustain themselves, the next stage requires *synchronized parallel* startup & operation of multiple PEC-interfaced WTs in a WPP [13], as a *voltage-controlled* island, possibly adapting microgrid control strategies [26]. During this stage, few BS-capable WTs can operate in grid forming mode, while others connect

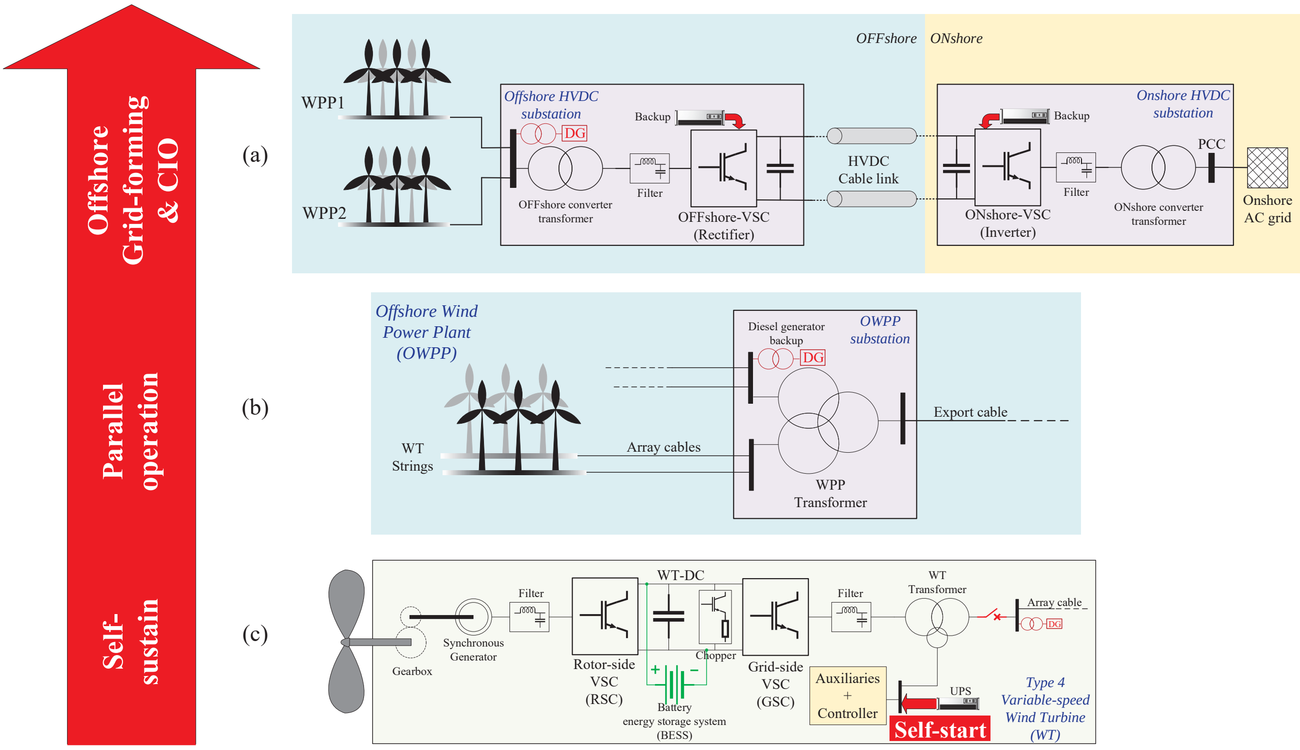

Fig. 1. Energisation sequence for blackstart restoration using offshore wind power plants (OWPP), with schematic diagrams of (a) VSC-HVDC connected OWPP-cluster (b) offshore wind power plant (c) full-scale power-electronics interfaced wind turbine

in grid-following mode to ensure effective & stable islanded operation followed by parallel power system restoration for increased voltage-stiffness [27]. The energy extracted from wind is then used to energize the array cables and the WPP-transformer, to prepare for the next stage.

4) Offshore Grid Forming: With the ultimate aim being connection of the OWPP to the main onshore grid to facilitate restoration and block-load recovery, the next stage consists of *coordinated parallel operation* of multiple WPPs in a cluster to form the isolated offshore collector-grid in a controlled manner [12]. This is required to effectively emulate stiff voltage source behaviour for charging the export cables & energizing the converter-transformers, while sharing the WPP-substation auxiliary loads, followed by VSC & HVDC-link energization.

5) Controlled Islanded Operation (CIO): Finally, it is necessary to ensure the stability & robustness of the islanded operation of the OWPP and the offshore grid. The objective of this stage is thus to maintain voltage & frequency stability especially during large load-pickups & WT-connetion/disconnection transients, along with robustness to different fault-scenarios (in offshore & DC grids), harmonic instabilities due to the PEC-interface [28] and HVDC-link resonance issues [29]. Once stable CIO of the OWPP is guaranteed, connection to the main onshore-grid can be done.

B. Challenges

Most modern WTs can do *self-startup* using the on-board (internal) UPS [13], [23], and already include some kind of local energy storage for control & measurement equipment power-up, emergency braking, and yaw & pitch actuation.

After start-up, the challenge is to energize the WT-DC link for VSC-operation and then generate a stiff voltage, to energize the WT-transformer & deal with the magnetic inrush currents by controlling the WT-GSC with support from local energy storage or the backup supply, if required. Moreover, the WT output power should be limited (*power-curtailment* at high wind) to prevent rotor-overspeeding, because the load is not sufficiently large to consume the additional active power [13], [30].

The next major obstacle is to operate several WTs in harmony to control the steady-state & transient voltage issues such as over-voltage & harmonic distortions due to the magnetic inrush currents of WPP-transformer energization and the initial charging currents of long unloaded-array cables, that impose demands on reactive power capability of the WTs [11], [15], [16]. At the same time, the PEC control should deal with WT-connection/disconnection switching transients, harmonic instabilities & non-linear load sharing, while managing the on-line WTs in a *coordinated parallel-operation*.

Morevoer, a weak offshore grid and the highly non-linear loading due to energization of long export cables, filter banks & HV-transformers [31] poses a risk of operation of protection devices that can trigger re-blackout. Thus well-planned and clearly defined guidelines for energisation of the network are needed. Additionally, a large number of WTs need to be operative in STATCOM mode to provide the reactive power required during the starting transients by the LCC/DRU, if used in place of the offshore-VSC [23].

Finally, the biggest constraint faced by WPPs being used for BS is the inherent fluctuating nature of the wind energy resource leading to a high availability uncertainty, for which energy-storage support along with down-regulated/de-loaded operation is required [11].

C. Control Strategies

Independent active (P) & reactive (Q/VAR) power control, effectively current (I) control, along with direct voltage (V) & frequency (f) control is necessary for BS&Is capabilities in OWPPs [6]. This section gives a brief overview of the relevant control strategies existing in literature, that can be used for the BS-energization sequence using OWPPs, as shown in Fig. 1.

1) Self-Start & Self-Sustain: Currently, WTs rely on an on-board power supply (UPS) for powering their controllers for small durations [13], [23], but require a larger energy storage, connected at the WT-DC link [11], [32], for the initial energization of the yaw & pitch mechanisms to be able to continue producing power with the WT's own auxiliary loads (1-5% of rated capacity) as the only consumption. The *idling* & *power-curtailing* modes can be used for supplying the low power internal auxiliaries and charging the DC link. Additionally, the WT must manage the production of the minimum and fluctuating power due to fluctuations in its own loads and varying wind speeds [13].

2) Grid Forming: Unlike the traditional LCC-HVDC system, the VSC-HVDC system does not require generation capabilities at both ends of the link for operation, which allows *top-down* restoration of remote OWPPs/islanded grids after a transmission power outage, by importing power from the healthy onshore-grid [4], [7], [33] and operating the offshore-VSC in *grid forming* [18] mode while the WTs connect in *grid-following* [18] mode [11], [13]. However, by controlling the WTs as a voltage source powered by the wind, it is possible to form the *islanded* offshore collector-grid in a controlled manner [12] without dependence on external grid-forming units, and thus, facilitate *bottom-up* restoration of the onshore-grid using BS-capability of OWPP. WTs equipped with grid-forming capabilities also enable *offshore* HVDC-rectifier energization as opposed to the conventional *onshore* HVDC-inverter energization [10], [23].

During grid-connected operation, the onshore-VSC is operated in *grid-following/supporting* mode [18], which requires an active onshore grid to which the VSC can synchronize [10], [12]. However, during BS conditions, the AC network is passive as no generation is connected, so the VSC must effectively operate as a UPS in *phasor-control* or *synchronous-machine emulating* mode to control the AC-V (amplitude & phase) and f [21]. This control mode is also used for operation with a very weak AC network connection, isolated wind parks, and during quasi-islanded or islanded conditions with relatively little or no generation online [21].

For BS-capability in OWPPs, the WT-RSC controls the WT-DC link voltage so that the WT-GSC can be controlled as a voltage source to control the offshore AC-V & f. The offshore-VSC (rectifier) then controls the HVDC-link voltage [10] while the onshore-VSC (inverter) controls the P, Q injected into the main onshore-grid, when connected. However, when a DRU replaces the offshore-VSC, the HVDC-link voltage is controlled by the onshore-VSC [31]. A distributed V, f control is presented in [22]–[24] for grid-forming operation of WT-GSC, especially in islanded mode when the main grid is not available.

To avoid dynamic issues associated with V-control, the WT must be controlled to absorb the generated VAR when energizing the unloaded lines [11], [16] and do gradual buildup of the AC-V to minimize the transformer in-rush current [21]. The PEC-interfaced WT can provide Q-compensation during steady-state, dynamic and transient conditions to support the power system restoration procedure, behaving in a way similar to a STATCOM [34], [35]. Moreover, the length of line energized & the size of transfomers needs to be considered to optimize the restoration process as energizing a small section prolongs it while a large-section risks damage to the equipment insulation. Finally, coordination between the HVDC link start-up and the restored AC system strength is necessary as a certain strength of the AC transmission system is required to absorb the startup impact of the HVDC link, else the system can collapse or even suffer re-blackout [36].

3) Parallel Operation: Control strategies developed for microgrids can easily be extended to the case of large OWPPs, taking into account their specific system characteristics [22]. In microgrid islanded operation, VSCs are responsible for f-control & V-regulation. *Single*-master operation (SMO) or *Multi*-master operation (MMO) [27] with a *3-level hierarchical*-control structure [26], can be used to coordinate multiple WTs in a WPP on the lower level and multiple WPPs in a cluster on a higher level, to emulate a *stiff & controlled* voltage source.

The lowest *inner* level consists of the inner V/I-control loops to emulate V/I-source behaviour of the VSC and provide maximum power point tracking, power limitation, fault ride-through and power-quality enhancement capabilities [26]. The next *primary* level consists of the *droop*-control to mimic synchronous generator behaviour, add synthetic inertia & avoid large circulating currents between paralleled PEC-based sources, without using any critical communication [26]. Although this scheme provides high reliability & flexibility, it also has several drawbacks such as power sharing transients due to output impedance, non-linear load sharing issues, load-dependent f-deviation and inherent tradeoff between P/Q-sharing & V/f-regulation [26].

Thus, *secondary* & *tertiary* control levels along with *harmonic* current-sharing techniques are required to restore the deviations produced by the virtual-inertias & output-impedances and avoid circulating distortion powers [26]. Additionally the *virtual-impedance* loop helps control the output impedance and allows intelligent transition between V-control & PQ-control modes of VSCs, which helps take advantage of fast VSC-operation while avoiding large transients due to smaller output impedance [20], [27]. The *secondary* & *tertiary* levels also provide grid-synchronisation control, low-voltage ride-through and help improve power quality & V-stability at the point of common coupling (PCC) with the onshore-grid [26]. Moreover, droop-control independent of the offshore-grid characteristics, obtained by using the WT-RSC to control WT-DC link voltage, can provide robustness to set-point changes, dynamic voltage-issues and connection-disconnection transients during BS-energization [22].

It is also beneficial to have a *sectionalizing strategy* to pre-plan the WT-islands in the OWPP during the energization & synchronization process, based on conditions such as BS-availability & capability, generation-load matching, grid-forming capabilities with load-pickup etc., to use the OWPP optimally for parallel power system restoration (build-up) [19], [37].

4) Controlled Islanding: Networks with a large number of PEC-interfaced units face many challenges to maintain stability [38] due to *harmonic-instabilities* [28] and substantial *network-configuration changes* [20] from moderately strong AC to weak & extremely-weak AC, islanded & passive networks.

The wide timescale control dynamics of VSCs can result in cross couplings between the electromechanical dynamics of electrical machines and the electromagnetic transients of power networks, which may lead to oscillations/*harmonic-instabilities* (due to negative damping of the control output admittance) across a wide frequency range, depending on both the specific controllers of the converters and the power system conditions [28].

When moving to islanded operation or when a large load is connected during islanded operation, the initial high imbalance between local load & generation may lead to large f-deviations & transient overloads. However, due to economic reasons, VSC overload capacity is limited and thus intelligent control is required to mitigate the transients and maintain stability [38]. Thus, during restoration, the allowable size of load pick-up should be lesser than the rate of response of prime movers already on line [16] to keep the f within acceptable limits, and a minimum load pick-up time interval should be ensured to allow the system to come back to a stable operation state. A *coordinated virtual-inertia* based control strategy has been proposed in [30] to utilize the WT to maintain the the isolated system-f, and thus enhance the f-stability during power system restoration. Additionally, most studies on VSC-HVDC control strategies are based on ideal conditions with balanced AC-V and so it is necessary to improve the VSC-HVDC system performance when WPP-V is unbalanced since faults are inevitable.

Trajectories of the system eigen-values and the load step-sizes can be used to assess the stability of the target states, and the position of the largest eigenvalue gives a measure of the stability margin of the system [39]. *Input-admittance matrix* or *impedance-based* system modelling can be used for stability analysis with generality [40] and stability can be guaranteed by making sure that the VSC dissipates power (non-negative conductance) at critical frequencies, particularly poorly damped resonances [41].

Finally, since WTs use wind as the resource for power production, they have an inherent variability and availability-uncertainty that lead to inherent reliability issues, although the variability decreases over a larger area and the availability-uncertainty, farther from the shore. Thus, energy storage can help improve reliability without having to increase spinning reserves [21]. Moreover, a *capability assessment* is needed to help ensure steady power production, strong grid-forming and stable islanded operation by the OWPP for supporting the TSO in the upstream onshore-grid BS-process. Thus, ultimately it is important to assess the variation of V-stiffness with weather fluctuations.

IV. Conclusion

The factors discussed in the motivation section show that equipping OWPPs with BS&Is capabilities is beneficial for improving the operational reliability, stability and security of the future power system with a large volume of RES. An energization sequence to achieve BS-restoration using OWPPs has been proposed in this paper, along with the major technical challenges faced during the different intermediate target stages. Finally, the control strategies for *grid-forming*, *parallel-operation* and *controlled-islanding* of WTs in OWPPs have been presented. These allow the OWPPs to be used as BS-units and facilitate grid-restoration after a blackout, thus helping minimize the restoration time & the unserved load.

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