Functional Requirements for Blackstart and Power System Restoration from Wind Power Plants

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***Abstract*—In the recent years, the worldwide grid integration of renewable energy sources (RES) has grown rapidly. However, the grid-integration of large volume of renewables like wind and solar, interfaced by power electronics converters, is changing the dynamics of the power system and creating challenges to maintain reliability, robustness and stability of electricity supply. Morevoer, the stronger inter-linking of networks poses a greater risk of wide-area blackouts. With the growing share of wind power in the grid and conventional generators being phased out, large offshore wind power plants (OWPP) with state-of-the-art wind turbines (WT) can provide services of blackstart and power system restoration (PSR) in the future. This paper provides an overview of the technical requirements of blackstart units and the current capabilities of WTs, based on grid-codes, studies on ancillary services and recent blackout experience. Finally recommendations to the functional requirements of WTs are made, to make OWPPs capable of blackstart and help facilitate PSR in the future.**

I. Background

The rapidly growing world population and the consequent rising demand for electric-power necessitates an increase in the installed generation capacity, while maintaining reliability of supply. In the face of environmental problems like global warming, coupled with increasing fuel prices and the global drive towards sustainable development & conservation of natural resources, power electronic converter (PEC) interfaced renewable energy sources (RES), such as wind turbines (WT) and solar-PV systems have gained wide popularity and are being adopted in power networks around the world [1], [2].

The European Commission has recently proposed a target of at least 27% renewables in the total energy consumption in the EU by 2030 to make the EU a global leader in renewable energy [3]. Along with the EU, many countries like USA, China, etc. have set out several energy strategies for a more secure, sustainable and low-carbon economy. The Australian government, for example, has set a RES target of 33000 GWh by 2020, which constitutes approximately 23.5% of the country's total power generation [2].

India is running one of the largest and most ambitious renewable capacity expansion programs in the world, with the latest target of achieving 227 GW of electrical power (earlier 175 GW) from RES, including a more than doubling (to 66 GW) of its large wind power capacity by 2022 [4].

Wind energy, due to its abundance and cleanliness, is the fastest growing RES, and shows huge promise for the future to be a major electricity source due to its decreasing price per kWh [5]. Moreover, due to onshore space constraints and poorer wind conditions, large offshore wind power plants (OWPP) with high power WTs have gained popularity and this has led to an increase in the share of offshore wind energy [6]. In India, the wind energy share is almost 50% of the total grid-interactive RES capacity at present, and in terms of meeting its ambitious 2022 targets, wind power is more than halfway towards its goal [4].

The next section of this paper presents the main factors motivating the need for development of blackstart (BS) and islanding capabilities in OWPPs, especially in regards to the future power system given the recent increase in blackout events. The following section then presents the current technical requirements for a generator to provide blackstart service, as enlisted in grid codes or formulated from studies on ancillary services. Section III then briefly lists the present WT capabilities to find the technological gaps in making blackstart restoration (BSR) by OWPPs a reality, which are then discussed in Section IV, ending with a short conclusion.

II. Motivation

The integration of a large volume of RES in the power system introduces new, variable & more unpredictable power flows, thus complicating the grid operation to maintain reliability, stability and security of supply [1], [7]–[9]. Moreover, the reacitve power (Var/Q) reserve in network decreases as conventional synchronous generators (SG) are replaced, destabilizing the long-distance transmission corridors between load-centres & large-scale RES (eg. MW-scale OWPPs) during system contingencies [2]. Additionally, inertial decoupling from the grid by the PEC interface without proper Var support, leads to violent frequency-swings, voltage-instability and over-burdened reserves, resulting in decreased transient stability [2], [9], [10]. Ultimately, this can cause cascaded tripping of generation and potentially trigger wide-area blackouts, especially in strongly linked networks [9]. Thus, future power systems might require blackstart and islanding capabilities in RES to support power system restoration (PSR) [5], [7], [10], [11].

A *total shutdown* leading to a blackstart is a *High Impact, Low Probability* (HILP) event, which whilst unlikely has a significant societal and economic impact since electricity is a basic need in today's world [12], [13]. The impact of a blackout increases exponentially with the duration of its restoration, which can be reduced by having more available blackstart units (BSU) and a well planned restoration process [14].

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In recent years, there has been a rise in the number of widespread blackouts around the world. For example, the North American blackout in August 2003 that lasted almost two weeks, and the European power outage on November 4, 2006 that affected 15 million people. The largest power outage in the hisotry, by the number of people affected (670 million), is the Indian blackout of summer 2012 during which the northern, eastern and north-eastern grids collapsed on 30 & 31 July [15]. It brought the rail-network, airports and businesses to a standstill, causing economic-disruption and chaos all across northern India.

As RES replaces conventional SG, it is being recommended to evaluate BS-capability of other power plants [16] and create new restoration corridors to increase the operative resources during PSR [17], [18]. The average running hours of conventional units is decreasing year after year due to the increasing penetration of RES, thus making BS-services from alternate sources more necessary [19]. Currently, after a blackout, 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 [20]. However, this is characterized by long startup times. In contrast, large VSC-HVDC connected OWPPs, with steady wind conditions far from the shore and composed of state-of-the-art WTs, can provide fast & fully-controlled [7], [8], high-power, environment-friendly BSR service with high availability [5], [20], [21] owing to the advanced functionalities of the VSC interface [22], [23]. Since BS capable OWPPs can help decrease the impact of a blackout by reducing the restoration time and the unserved load during the PSR period [24], blackstart & islanding 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 [21].

III. Status Quo

The power system restoration process consists of three stages, viz. re-energization of the network, voltage (V) & frequency (f) management and finally re-synchronization & load pickup [19].Typically a combined *zonal-backbone* restoration approach is used in most countries, as this allows for faster parallel restoration of different regional-islands while extending auxiliary supplies to non-BSUs through the skeleton/backbone, and so increasing the stability for large load pickup to enhance the restoration process [12], [19].

Normally, after a blackout event, non-BSUs (such as fossil fuel power plant) with large capacity have to be restarted & re-connected to the grid. Thus, BSUs with limited capacity (hydro/gas) restart immediately and energize the network between BS and non-BS units, to send cranking power to non-BSUs. Large OWPPs capable of *houseload operation* can energize the transmission corridor and pick up block loads directly, given steady wind conditions, which saves time as a non-BSU doesn't need to be energized from a limited capacity BSU.

Historically one large provider has delivered all the technical BS-requirements that are listed below in Section III-A; however these can also be met using a combination of providers to deliver the equivalent BS-service. This adds more resilience against events which may render one type of technology unable to startup (eg. gas shortage) and also alleviate reliance on specific transmission routes for energization and load-pickup activites [12].

With the changing generation profile due to increasing integration of RES, there is an increased number & type of sources that can assist with BSR. This section aims to identify the technical requirements for BSUs and if WTs can potentially become new BS-service providers. However, even if they are not able to deliver BS-service, WTs may still play a part in the later stages of restoration [12].

A. BS-Service Requirements

Restoring power after the loss of electricity supply can be difficult, as power stations need to be brought back online, which normally is done with the help of power from the rest of the grid. However, in case of large scale power outage or total shutdown/blackout, a blackstart needs to be performed to restart a generating station and restore power to the grid [25].

1) BS-Service Description: A BS-service is defined as a provider, or combination of providers who can meet the three basic requirements for BS viz. start-up independent of external supplies (following a total/partial shutdown), energize the transmission/distribution network and then provide block loading of local demand in a stable power island [12]. The BSU may also be required to provide crank-up power to other power stations and eventually synchronize to other power islands [12]. According to the ENTSO-E Grid Codes [26] Definition 45, BS-capability is the capability of recovery of a power-generating module (PGM) from a total shutdown through a dedicated auxiliary power source without any electrical energy supply external to the power-generating facility. Not all power generation have, or are required to have, BS-capability.

2) Asset Components: A BSU used for bottom-up restoration typically consists of 3 components [27]:

1) The *black-starter/self-starter*: an asset that can startup without supply from the grid eg. diesel generator or battery energy storage system (BESS), and then power the auxiliaries of a larger generating unit.
2) The *cranking path* between the self-starter & the main generating unit(s); the self-starter may be located on the same site as the unit (no cranking path).
3) The *main generating site*: responsible for re-energizing the grid and delivering the BS-service. The site may consist of 1 or more power and storage units, but overall must be capable enough to deal with the MW and MVar flows during PSR.

A BS-service provider may even consist of an aggregation of sites, but operate in a similar way to a single power unit providing restoration services [12], [27].

3) Minimum Technical Requirements: The main technical requirements listed here fundamentally describe the three significant activities undertaken during restoration viz. the ability to start-up independent of external supplies, the ability to energize part of the transmission network and the ability to pick up block load demand, while maintaining V & f within acceptable limits to maintain system stability. A summary of the major requirements and why they are required is given in Table I.

a) Self-Start: As per the ENTSO-E Grid Codes [26] Article 15.5, a PGM with BS-capability should be capable of starting from shutdown without any external electrical energy supply, within a time frame specified by the relevant system operator, in coordination with the relevant TSO. To provide a black start, some power stations are equipped with small diesel generators which can be used to start larger generators, that in turn can be used to start the main power generating units. Gas-fired plants, independent from industrial processes and large pump-storage plants, with high inertia & Var absorption capability, can be restarted quickly and are therefore suitable candidates for PSR [19]. If stored energy eg. BESS, is used to temporarily energize the auxiliaries of a main BSU that primarily uses another energy source, the minimum stored-energy should be sufficient to allow 3 consecutive black starts, and as soon as the main unit can supply its own auxiliaries, the storage should no longer be needed [19].

b) Var/Q Requirement: BSUs must be able to absorb the significant amount of MVar generated by the connection of grid elements like overhead lines & cables under low loaded conditions. For example, in Belgium, the current requirement is 30 MVar absorptive capacity for some regions, although this can be partly covered by shunt reactors installed by Elia (Belgian TSO) for reducing the requirement from BSUs [19]. For energizing the 380 kV backbone as part of the Belgian PSR plan, an absorption requirement of minimum 50 MVar at the low voltage side of the step up transformer, during low active power production, for example, is used as an indicative value [19]. The BS-Service Description by National Grid in UK requests at least 1000 MVar absorptive capacity for generators connected at 400/275 kV, although this depends on the local system configuration [12].

c) V-Management: The ENTSO-E Grid Codes [26] Article 15.5 states that, a BSU should be capable of automatically regulating dips in V caused by connection of demand, and control V automatically during the system restoration phase. The system should be re-energized at as low a V as possible to reduce the MVAr generation of unloaded transmission feeders. Soft-energisation is preferred instead of sequential energisation, as the de-energized transmission path can be built at a reduced V, in parallel to the BSU startup. However, the BSU must have the facility to start at a reduced excitation, else sequential energisation is done, in which the BSU starts up first followed by 1 transmission station at a time [28]. Soft-energisation is also used to reduce the magnetic inrush currents during the energization of the BSU step-up transformer, which can in theory, be up to 10 times the rated current and lead to V-dips [19], [28]. Once all generation stations are online, the transmission system & load should be restored feeder by feeder to limit the increments of MVArs generated by the developing system. Moreover, long high voltage (HV: 110/220/400 kV) transmission lines with an unloaded transformer at remote end should be energized with care as this is a possible resonant condition with resultant high overvoltages [28].

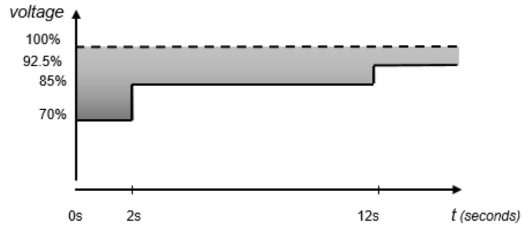

Fig. 1: Acceptable V-levels after taking up block loads, for Belgium [27].

d) f-Management: The ENTSO-E Grid Codes [26] Article 15.5 states that, a BSU should be capable of operating in Limited Frequency Sensitive Mode – Over/Under-frequency (LFSM-O/U) and control f in case of overfrequency (OF) & underfrequency (UF) within the whole active power output range between minimum regulating level and maximum capacity as well as at houseload level. To minimize V,f-deviations, the initial load restoration should be carried out in the smallest steps possible, and once a number of generators have synchronized, load should be picked up in steps appropriate to the size of the subsystem, starting with the nearest loads. The system-f should be controlled at minimum 50 Hz (preferably higher) before restoring any load, with one *swing* generator in the subsystem operating in isochronous control mode, while others in normal droop setpoint control mode [28]. Moreover, given the uncertainties about exact consumption after a period of non-supply and to cope with fluctuations in offtake of reconnected grid users, BSUs should not be operated near their maximum active power limit during the early PSR stages to have some upward reserve capacity in case of f-instabilities. For example, Elia in Belgium suggests to not exceed 70% of maximum power production [19], while EirGrid in Ireland suggests a limit of 50% [28]. Additionally, priority should be given to restoring supply to any generators that have tripped to houseload [28].

e) Block Loading or Active Power (P) Requirement: The ENTSO-E Grid Codes [26] Article 15.5 states that, a BSU should be capable of regulating load connections in block load. The instantaneous block-load demand is for example, at least 10 MW for Belgium (Elia) [19], [27] & 35-50 MW for UK (National Grid) [12], with power factor, PF$\geq$0.8 (inductive). During block-loading, the island-f should not deviate from a set range even temporarily, for example, 49-52 Hz for Belgium (Elia) [27] & 47.5-52 Hz for the UK (National Grid) [12]. Moreover, during load-pickup, V at the connection point should stay in the shaded operating range, as indicated in Figure 1 [27]. The BSU aimed at restoring the backbone has a typically higher requirement of minimum installed capacity than that covering a regional zone. For example, in Belgium at least 85-140 MW is required for restoring the 380 kV backbone, and 65-115 MW for a zonal restoration [19].

The main goal of a BS-service is to re-energize the critical connections, including high priority significant grid users and the auxiliary services for non-BSUs. It is important to keep available a P-margin to compensate for grid losses and cope with the fluctuations in offtake of reconnected grid users [27].

Technical Capability	**Need**
High availability on both the main & auxiliary generating plant (typically 90%).	System shutdown is an HILP event and could happen at any time.
Ability to start up the main generator from shutdown independently, without the use of external power supplies.	During BSR, the transmission system is not energized.
Ready to energize part of the transmission system within a certain time after instruction from TSO.	Faster energization means faster restoration.
Var capability to energize the immediate transmission/distribution system(s) and to withstand the magnetic inrush & transient voltages associated with this energization.	Energizing the local system is one of the first steps in restoring the network.
Capability to • accept instantaneous block-loading demand, and • control *V/f* levels within acceptable limits during block-loading process.	Ultimate aim of PSR is load recovery.
Ability to provide at least 3 sequential blackstarts.	To allow for possible tripping of transmission/distribution system as during PSR, stability is lesser than in normal operation.
Facilities to ensure • safe shutdown of all generating units without the need for external supplies, and • state of readiness for subsequent startups.	Multiple attempts may be required for PSR.
Back-up fuel supplies to enable the provider to run for a minimum duration following a BS-instruction.	Alternative fuel sources increase resilience in the restoration.

Tab. I: Major BSU technical requirements & why they are needed [12], [19], [28].

4) Fuel Supply: Once *V* has been restored on the HV-side of the step-up transformer, the BSU must operate for at least 24 hours whilst being subject to offtake fluctuations, and thus, there must be sufficient supply of fuel to start the service and last in operation [27]. As mentioned in Table I, some assets included in the BSU may be required to maintain a minimum stored energy volume at all times else the service would be unusable at the moment of a blackout. This is especially important in case of pump-storage units (sufficient water is needed in the upper forebay) and BESS (minimum state of charge must be ensured) to execute re-energization procedure [27]. Backup fuel supplies must also be present to enable the provider to run for a minimum duration following a BS-instruction, for example, 3-7 days in case of UK (National Grid) [12].

5) Synchronization: The ENTSO-E Grid Codes [26] Article 15.5 states that, a BSU should be able to synchronize within the system's *f*-limits and, where applicable, *V*-limits specified by the relevant system operator. Also, a PGM with BS-capability should be capable of parallel operation of a few PGMs within one island.

6) Islanding & Trip to Houseload (TTH): According to the ENTSO-E Grid Codes [26] Definition 43, the large scale *island operation* capability refers to the independent operation of a whole network or part of a network that is isolated after being disconnected from the interconnected system, having at least one PGM or HVDC system supplying power to this network and controlling *V,f*. On the other hand, *houseload operation* capability refers to the operation which ensures that PGMs are able to continue to supply their in-house loads in the event of network failures resulting in them being disconnected from the grid and tripped onto their auxiliary supplies, as stated in the ENTSO-E Grid Codes [26] Definition 44.

Just before an imminent blackout, protection systems disconnect the power plant from the grid, dropping production for feeding its own auxiliaries in houseload operation. Houseloaded non-BSU plants can re-synchronize to the grid and be used to re-energize a busbar as restart is not needed, and thus, can support the operator by speeding up the restoration process [19]. In order for restoration to be achieved, a number of BSUs use local demand to energize a pre-agreed Local Joint Restoration Plan, create small power islands [12], which when considered stable are resynchronized to pick up critical loads within target times [19]. The stability criterion for Belgium for example is, 350 MW load & at least 3 PGMs for regional islands (150 kV), and 1000 MW load & at least 10 PGMs for the 380 kV backbone [19].

The Tennet Grid Codes for High & Extra-high Voltage [29] specify in Section 3.2.8, the requirement for a PGM to be able to switch to houseload operation from any operating point and to islanded operation when disconnected from the grid. A PGM rated above 100 MW must be capable of islanding mode operation for several hours, if it is able to regulate the *f* under the condition that the resulting capacity deficit is not greater than the primary control reserve in the island, and in case of a capacity surplus, the PGM must be able to down-regulate to the minimum capacity. Houseload operation should be maintained for at least 3 hrs, and the PGM must be able to balance sudden consecutive (minimum 5 mins interval) load connections (10% of nominal load, maximum 50 MW) in islanded operation.

7) Restoration Times: After an alert has been issued, the system operator has a list of times that are proposed to achieve the targets set in the restoration plan. For example, the Belgian TSO, Elia aims to achieve re-energization of 90% of the connection points within 24 hrs by using target times as mentioned in Table II [27]. Given approximately 800 substations to supply Elia's connection points and 6 dispatching consoles in 3 control centres, an intensive parallel operation is required to from each console to energize 120 substations in 24 hrs to achieve the 90% target [19]. National Grid, UK has also set up strategies for achieving an average restoration time across the year of 24 hours to restore 60% of national demand, provided an economic &

State Description	**Max Time (in min)**
Diagnosis phase (Time needed to establish nature & extent of blackout)	30
BSU Startup time (between instruction to launch the BS-service, and re-energization i.e. main generating site is available to accept load)	90 for hot-start[1] 180 for cold-start[2]
Restart time of non-BSU (hot state, houseload failed)	65 (not for nuclear plants)
Restart time of non-BSU (houseload operation)	10; 30 (for nuclear plants)
Restoration procedure (energization of one switchyard)	10
Time per block-load (5 MW; 10 MW if stable backbone)	2

[1] a unit that was operating just before the blackout occurred.
[2] a unit that was in shutdown mode just before the blackout occurred.

Tab. II: Estimated restoration times for Belgium (Elia [19])

efficient procurement plan, with the following target times (from plan formulation) [12]:

- 1 hr – stable operation of BSU.
- 2 hrs – BSU ready to energize at least part of total system.
- 4 hrs – load restored to subsystem.
- 6 hrs – re-synchronization of separate subsystems.
- 12 hrs – restoration of continuous supply to all remaining 400/220/110 kV transmission stations.

B. *WT Capabilities*

The ENTSO-E Grid Codes [26] indicate that the BS-capability is technically possible on larger PGMs of type C & D (Articles 15.5 & 16.1), AC-connected offshore power park modules (Article 27) and also pump-storage units. The Network Code on Electricity Emergency and Restoration [30] broadens the BS/PSR service providers to include smaller PGMs of type A & B, and energy storage units of the concerned significant grid users, as part of aggregations of assets that together deliver the service (Articles 2.1, 2.3, 2.5 & 4.4). The *top-down* [27] BS-capability of HVDC systems is also included in the Network Codes on HVDC [31], to re-energize a busbar on the *dead* TSO-side, assuming the other TSO-side is still energized (Article 37).

Today, mainly large thermal or pump-storage units provide BS-service in most European countries, to meet the severe technical requirements, as enlisted in Section III-A, which typically cannot be provided by smaller units or by intermittent units. Currently, due to security reasons, nuclear plants are considered as critical loads that must be re-energized as quickly as possible, although they can contribute to the restoration by absorbing Var and providing stability to re-energize the backbone [19]. Energinet.dk in Denmark also uses the VSC-HVDC interconnector to Norway for BS-service, after assessing the probability of not being able to import power from Norway in case of a blackout in Denmark, to be low. Similarly, Ireland uses an HVDC interconnection with Great Britain for BS as the philosophy of the Irish BS-services indicates a lower requirement on availability per service combined with the procurement of more services [19].

Although for the moment, intermittent production units (like wind, solar-PV) are not considered as proven technology for grid restoration, there is a potential to open up the delivery of the service to alternative configurations like aggregations of units. Also it is not excluded that energy storage systems (ESS) could facilitate participation of intermittent production to restoration services in the future [19]. This section presents an overview of the advanced control functionalities provided by modern WTs that can potentially meet the BS-service requirements discussed before in Section III-A.

1) Grid Codes: Very few countries like Denmark, Germany, UK, Spain and Ireland have WPP specific technical regulations [32]. Neither the codes of individual countries nor ENTSO-E define requirements relating specifically to offshore AC systems separated from the synchronous grids by HVDC systems, but the requirements are passed through to the WPP & associated turbines and therefore apply to offshore AC systems [33]. Except for Germany, the technical specifications for the connection of WPPs into the transmission system do not form part of a specific grid code and can be found in official documents listed in [25] Table 4.1. According to the Danish Grid Codes [34] and Tennet Grid Codes for Offshore [29] and High & Extra-high Voltage [35], WTs are required to have control functionalities like f-response (like P-reduction during OF), PQ-control, V-control, PF-control; ramp rate constraints; behaviour under grid-disturbances like V-dip tolerance (LVRT), power-quality requirements (DC content, asymmetry, rapid V-changes, flicker, harmonics & distortions), and System protection. However they are exempt from f-stability and restoration services.

a) Var Requirement: Major blackouts have been caused due to V-instability as a consequence of insufficient Var reserve in power networks [2]. Almost all the grid codes reviewed in [2] like Australia, Denmark, Germany, Ireland, Spain & the UK, specify steady-state & dynamic Var requirements for WTs. During V-dips, the Fault Ride Through (FRT) mode of WTs allows them to suspend their normal steady-state control and perform a sequence of actions to remain connected to the grid for providing support to V-recovery at the point of connection (PoC) [36]. The superior Var-control & stability improvement capabilities of WPPs, like Voltage Ride Through (VRT) & Reactive Current Injection (RCI), is increasingly being demanded by grid codes, as reviewed in [32], [37], [38], to support network stability under various grid-disturbances [2].

b) V-Management: VSC-HVDC connected OWPPs can provide advanced V-control & V-support functionalities. In a study on the use of large scale OWPPs in PSR plans, the offshore OWPP-VSC has been shown to contribute significantly to V-control, by responding very fast to increasing Var demands due to energization of new lines [13]. Local Voltage Control requirement for offshore-WPPs is expected to be included in the future grid codes, of especially Spain & Germany [32].

c) f-Management: In high wind power generation areas, f can increase very fast if power system inertia is not high, which causes the automatic OF protection system to trip conventional generators leading to f-instability. Thus, the fast (down-regulating) P-control capability of modern WPPs, owing to the PEC interface, can be used for creating a spinning reserve margin [13] and is a relevant option in the future defence plans for primary frequency regulation (PFR) purposes [1], [13]. Fast Frequency Response (FFR) from WTs by using the kinetic energy of the rotating mass of the machine, can help reduce initial $\frac{\mathrm{d}f}{\mathrm{d}t}$ (RoCoF) but not support overall PFR [39]. Compulsory Inertia Emulation & Power Oscillation (0.15-2 Hz [2]) Damping requirements for WPPs are expected to be included in the future grid codes, of especially Spain & Germany [32].

2) WPPs in PSR: The startup time of WTs is about 40 sec & wind generation power pickup time is 30 sec, compared to 20 min for thermal units & 5 min for hydraulic units. However, currently on-shore WPPs do not contribute to restoration plans due to the operational & control challenges owing to the intermittency of wind and the difficulty to cope with wind variation & f-control [19]. Additionally, although commercially available offshore WTs can blackstart and power their own auxiliaries, intermittent production is technologically not ready to re-energize the cable between the offshore platform & the onshore station within V-limits, regardless of availability at the moment of blackout [19]. However, innovative solutions for BS-services by OWPPs show potential for the future [27]. Moreover, at the beginning of PSR, the isolated small network is not complete & strong enough due to the generators just restored not located in the stability domain. Thus, if *grid following* [40] WPPs connect at this stage, a second blackout can occur when there is a large fluctuation of wind farm output power. For WPPs to participate earlier in PSR, *grid forming* [40] WTs are needed.

Most articles in literature focus on the technical regulations regarding the connection of large WPPs to the HV-transmission system and the enabling technologies that have been suggested for various types of WTs, to comply with the latest international grid code requirements, including P-control, Var support, V-regulation, f-control, FRT, inertia response and power system stabilization [37], [38]. However, there is not much yet on using OWPPs for PSR, especially in the earlier stages. The next section lists some recommendations based on blackout & system restoration case studies to help OWPPs support the TSO by contributing to PSR.

IV. Future

1) Main Challenges: According to a survey of operator needs during PSR, the most common priority was found to be ensuring stable supply capacity via BSUs or interconnectors/TTH and supply other generators to restore priority loads (like hospitals, mines, railways, industries, government institutions, airports, etc.) which stresses the need for some sort of storage in WTs [17]. A high *power* density ESS (supercapacitor/flywheel), located at the WT-DC link, can provide initial excitation & handle DC link capacitor charging transients, while a high *energy* density ESS at the PoC may be used for long term power management [23].

For onshore WTs, a small diesel generator or a BESS must be installed to supply the auxiliary loads and the grid-side PEC must be designed with *grid forming* [40] capability to be able to operate in a weak network. For offshore WPPs, currently backup diesel generators on the offshore substation platform are used to supply auxiliaries (air-conditioning, oil pumps, emergency lighting, etc), however other options should be considered to minimize use of diesel and provide cost benefits. For example, few *blackstart-able* WTs can be used to energize the array/export cables & power all the auxliaries in the OWPP [33]. This requires *grid forming* [40] control of grid-side PEC and changes to the rotor-side PEC & turbine controls. Note that most recent WTs are already close to be able to handle the MVars produced by the array-cables' energization. Moreover, the inductance of the WPP transformer offsetting the capacitance of the cable can make it easier for WTs to blackstart the offshore-platform [19]. However, a large gap to bridge is the energization of the cable to the onshore-substation while meeting the grid code requirements in terms of V,f-control during PSR, as mentioned in Section III-A. Shunt reactors or other compensation devices can also be used to mitigate the Var absorption requirements of the WTs, especially in case of long electrical distance between BS-station & PoC (kilometres of cables/overhead lines) [27].

Furthermore, WTs must be able to deal with the inrush currents and the transient busbar over-V [41], due to over-excitation of transformers, generator underexcitation, or even self-excitation, harmonic resonance, etc. [18], in a controller manner. Additionally, the lines mustn't be fully compensated to avoid the risk of resonance at 50 Hz with consequent over-V [41]. Then there is always the challenge of meeting block loading demand with an intermittent availability [19]. Lastly, Ferranti effect at HV when energizing large distance lines between generating stations & load centres can cause V-surges when energizing power transformers.

An initial study on the use of large scale OWPP within PSR plans, modelled as *grid-following* current source (dynamic PQ-injector), has been done in [13], while [42] shows the potential BS-capabilities of OWPPs, if controlled as a *grid forming* voltage source. Finally, coordinated control of WTs must be included in the WPP controller to be able to control V,f in a weak network. BESSs can be used to mitigate the intermittency issues of wind energy, however, in absence of wind, the BS-capability will come only from the BESS [19].

2) Protection Settings: As an example, based on the study by Australian Energy Market Operator (AEMO), sustained damage & tripping of 275 kV transmission lines by 2 tornadoes in South Australia (SA) in September 2016, followed by a sequence of faults resulted in 6 V-dips over a 2 min period in the SA grid. This activated the (overspeed) protection feature resulting in a sustained power reduction of 456 MW from 9 wind farms in less than 7 sec. This ultimately led to system separation and V,f-instability in Uncontrolled Islanded Operation (UCIO), causing a blackout. According to AEMO, changes made to turbine control settings shortly after the event removed the risk of recurrence given the same number of disturbances, and AEMO's modelling indicates that without the generation deficit, UCIO would not have occurred and the blackout could have been avoided [36]. This makes it important to redesign the protection settings for defence against extreme contingencies especially in areas with high penetration of wind power generation or island systems like Ireland/Australia [1].

3) Controlled Islanded Operation (CIO) & TTH: Continuing with the above mentioned example of the 2016 SA Blackout, about 700 ms after the wind farm power reduction, a Special Protection Scheme tripped the interconnector due to transient instability (loss of synchronism) and caused *islanding* (separation) of the SA power system. However, without any load shedding, the remaining generation was unable to maintain the islanded system-f leading to UCIO, ultimately ending in a blackout. AEMO suggests practical measures to be implemented for stable CIO, like inertia emulation from WTs to slow down the initial RoCoF and increase in local f-control services like PFR (spinning reserve margin) from WTs [36].

The houseload operation capability of a plant is not used in the restoration strategy in most cases, except France, due to the uncertainties on the root cause of a potential blackout and other risk factors [19]. However, OWPPs that can switch to TTH mode and do CIO of offshore island or a regional onshore-zone [12] can provide short term early stage PSR support and also defend against f-instability following major loss of generation or imminent instability between areas (sudden tie-line power changes) [1], [27].

The authors have presented an overview of the control solutions to tackle the technical challenges for the different stages of blackstart & islanding capabilities of OWPPs in [43].

4) Intermittency Risk: The study by AEMO on the 2016 SA Blackout [36], mentioned before, discusses a scenario (Appendix M.2) with no WPP power reduction due to multiple V-disturbances, but assuming a loss of 200 MW of wind generation due to WTs shutting down (protection from excessive mechanical stress) during high wind speeds (above 90 km/h) immediately afterwards. Simulations carried out by AEMO demonstrate that the SA power system would have remained stable and interconnected under these conditions [36]. Thus, the wind intermittency & excessive speeds was not a material contributor to the blackout event, as out of the 456 MW wind power reduction, 35 MW of WTs disconnected due to high speeds during the last 5 V-dips. However, to better manage the risks to power system security, further investigation is needed of transient (0-6 hrs) power reduction from multiple wind farms during faults, wind turbine overspeed cut-outs during high winds, or rapidly changing winds in areas of high wind farm concentration [36]. This is a complex prediction in terms of modelling methodology.

It is important to mention here that, since BSUs are used for kick-starting the PSR from a totally de-energized state, their impact is limited to only the first 4-6 hrs of the restoration process. Once the system is kick-started, other factors, that are outside the influence perimeter of the TSO, determine rest of the PSR procedure [19].

Moreover, using intermittent generation early in PSR process will be an option for TSOs familiar with dealing with a high share of intermittent generation on a daily basis like Denmark, Germany, Spain, etc., despite the additional layer of complexity, as it is expected that flexible plants such as gas or hydro units will be already connected to the system to provide sufficient inertia and up- & down-ward reserves [19].

5) Fuel Supply: Currently, diesel generators are used on the offshore platform for supplying auxiliaries, along with backup diesel generators in case the first generator is not able to startup. Moreover, it is costly to ensure a constant fuel supply on the platform. Similarly, wind resource is intermittent, but larger MW-scale WPPs farther away from the shore with steadier wind conditions, can reduce the availability uncertainty. Moreover, having for example, just 10/20 *blackstart-able* WTs in a WPP to power up the auxiliaries, can provide more reliability & cost benefits with proper planning, compared to only 2 diesel generators, in the scope of PSR. It is also important to note that the requirement for maintaining 24 hr operation, as specified in Section III-A4, is not applicable to pump-storage BSUs, and soon after their startup, non-BSUs are synchronized along the restoration path to prevent exhausting the stored water volumes at the pump-storage plants [27]. A similar relaxation in the grid-codes can also help develop BS-service technology in OWPPs.

6) Grid Codes: Grid code requirements have been a major driver for the development of WT technology [37]. Similar to Var requirements now becoming mandatory for RES (eg. wind farms) due to Var-compensation & V-stability being major concerns for operators in case of high share of RES, restoration grid codes with participation from OWPPs are also needed [2].

Current WT technology, particularly developed over the last years, has been heavily influenced by the grid code technical requirements for the connection of wind farms to the power systems, to provide them with the control and regulation capabilities, necessary for the safe, reliable & economic operation of the power system [32].

In the short term, significant levels of wind generation in the system are now able to integrate into restoration plans and for example, National Grid in the UK is liaising with developers as to how restoration could be facilitated through services like Islanding & TTH operation by OWPPs [12]. However, an ongoing dialogue between TSOs & the wind industry is needed to understand how WTs can contribute to restoration in the long term [12].

V. Summary

The changing network paradigm with increased penetration of large RES necessitates the change in restoration procedures also. In the new generation mix, where conventional power stations are frequently out of service in order to accommodate large amounts of wind power, the number of generation units for the restoration phase can be limited due to their startup & grid-connection time constraints. Thus, in addition to hydraulic or gas turbines, used in initial stages of PSR, large OWPPs that currently offer enhanced control capabilities and high flexibility, can be valuable candidates to facilitate the PSR procedure. In this paper, a review of BS-service technical requirements has been compared to the current WT-capabilities, based on which recommendations are made for wind power to participate in restoration. Finally, development of standards for testing from the level of the component up to the entire WPP, is required for grid code compliance verification.

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