Delivery of frequency support and black start services from wind power combined with battery energy storage

Mikkel P. S. Gryning
Ørsted Offshore
Gentofte, Denmark
migry@orsted.dk

Bertil Berggren
Hitachi ABB Power Grids Research
Västerås, Sweden
bertil.berggren@hitachi-powergrids.com

Łukasz H. Kocewiak
Ørsted Offshore
Gentofte, Denmark
lukko@orsted.dk

Jan R. Svensson
Hitachi ABB Power Grids Research
Västerås, Sweden
jan.r.svensson@hitachi-powergrids.com

***Abstract*— The increased use of power electronic converters in electric grids leads to lower inertia of the system, and consequently a larger rate of change of frequency at faults. This in turn challenges the security of power supply and grid resilience in electrically isolated geographic regions. Therefore, there is a need to provide frequency support as ancillary service to TSOs as well as black start service from renewables. Black start service requirements are being introduced by TSOs, and this paper estimates the battery capacity required for black start given historical wind data for a reference wind power plant while upholding the service availability requirements. Moreover, the required frequency support and inertia provision capabilities of a wind power plant with battery energy storage system is analysed with respect to energy and rating. The implementation of two frequency support functions: inertial response control and fast frequency containment (droop) control is discussed.**

Keywords—Battery, wind power, capacity, black start, inertia, UK.

I. INTRODUCTION

A total or partial shutdown of major electrical transmission systems is an unlikely event due to the careful contingency planning of the Transmission System Operators (TSO). If a transmission system is operated such that it always can withstand an unexpected failure or outage of a single component or generation facility it is considered to have an acceptable security level according to the N-1 criterion [1]. Security assessment consists of both dynamic and static analysis on a network model to verify bounded operation for multiple sets of contingency scenarios, e.g. the loss of the largest generator in the network. However, the character of power systems is changing due to the introduction of long HVAC cables, HVDC connections, widespread penetration of renewable energy sources (e.g. photovoltaic plants, wind power plants) and offshore electrical network development.

The displacement of conventional generation by power electronic converter-connected resources reduces the total rotational inertia in the power system, which changes the frequency behaviour in case of disturbances. This causes new challenges to the security of operation, and it provides incentives to explore new ways to support the frequency. To alleviate both the underlying issue and potential consequences, a market for frequency support services is introduced. One way is to introduce new system services such as inertia emulation control and fast frequency (droop) support which can be provided by some grid connected converters, e.g. as discussed in relation to battery energy storage system.

After a power system blackout, the system is energized again by using a black start functionality. Black start is defined by National Grid in UK as the ability to start up the main generating plant of a power plant from shutdown without the use of external power supplies and be ready to energise part of the transmission system or, if appropriate the distribution network.

To fulfil the grid codes and grid services required of future offshore wind power plants (OWPPs) and at the same time optimize the operation of the plant, the IBESS concept has been proposed [2]. IBESS stands for Integrated Battery Energy Storage and STATCOM and integrates reactive power provision and battery energy storage functionality. Moreover, an active power filter function to reduce the harmonics in the point of common coupling together with an active mitigation of oscillations in the OWPP are integrated into the IBESS concept.

Interesting ancillary services from OWPPs that increase the revenue stream are black start, virtual inertia, grid frequency response, active filtering, intra-day balancing, short-circuit infeed, island frequency response, OWPP auxiliary supply and soft charging [3,4,5].

In this paper, the focus is on the ancillary services on black start and frequency support to determine the needed energy storage size and power rating. The outline is as follows: Section II analyses the black start delivery from OWPPs; Section III presents the frequency support from OWPPs. Finally, conclusions are drawn in Section IV.

II. BLACK START DELIVERY FROM OFFSHORE WIND POWER PLANTS

A. Requirements for Black Start

The black start service under investigation is inspired by the technical requirements stated for the" Black Start Competitive Procurement Event" by National Grid Ltd. in late 2019. The technical requirement document, "TD1 Technical Requirements & Assessment Criteria" [6], which outlines the following technical requirements that a provider must meet to be eligible for participation:

1. Time to connect less than 2 hours
2. Service availability $\geq 90\%$
3. Resilience of supply (continuous delivery of black start) ≥ 10 hours, t_d
4. Resilience of supply (ability to start delivery) ≥ 72 hours, t_{sp}
5. Block loading size ≥ 20 MW, P_b
6. Reactive capability ≥ 100 MVAR leading
7. Sequential black starts ≥ 3 $n_{restarts}$
8. Inertia value ≥ 800 MVA.s (real or virtual)
9. Short circuit level 240 $\frac{MVA}{\sqrt{3}U}$ kA (t<80ms), and 10 $\frac{MVA}{\sqrt{3}U}$
10. Frequency control able to keep frequency between 47.5 Hz to 52 Hz when block loading.
11. Voltage control within acceptable limits during energization and block loading ($\pm$ 10%)

Above requirements mimics the existing restoration strategy [7] with alleviating factors such as (8) allowing for virtual inertia, enabling power electronic connected devices such as type-4 wind turbines and batteries [8]. System restoration is a contingency scenario for the transmission network and (3), (4), (7) and (10) reflect the expected frequency stability, failure to restore sections of the network in first attempt, and that coordination of resources and system operation can take up to 72 hours. Requirements on short circuit level, voltage control and reactive capability exist to ensure the capability of the black start service provider to energize nearby substations with a high reactive load. For black start provision analysis, the requirements are segmented into energy requirements and converter rating requirements for steady state analysis. The specifications of (2), (3), (4), (5), (7) and (8) are associated with the energy storage of the IBESS, while (5), (6), (8) and (9) govern the converter rating. Transient performance requirements for frequency control (10) and voltage control (11) during energization and block loading is investigated in [9].

Purposely requirements are specified as minimum values and service providers are incentivized to deliver in excess of the minimum to attain a higher priority for service activation. The technical abilities of the service provider, e.g. block loading size and inertial contribution, will be scored in the tender process. The assessment method is divided into 30/70 for technical and commercial evaluation respectively, with the technical assessment method valuing active and reactive power output magnitude and continuous power delivery duration highly, while the commercial assessment focus on cost of delivery. The service payment for black start is per MWh delivered to the network.

For an IBESS associated with an OWPP a trade-off between service availability, power output and duration must be made. Active power output magnitude, i.e. block loading size, was for the analysis selected to range from 20 MW to 50 MW to cover both the minimum technical requirements and to explore service availability implications. The requirements for standby and delivery time was kept to minimum technical requirements.

B. Offshore Wind Power Plant Topology and Losses

The reference OWPP collector network design is based on a 66 kV multi-radial array structure connected to a 66 kV/275 kV grid transformer at the offshore substation. A long (50 km+) HVAC export cable provides the connection to shore with adequate harmonic filtering and reactive compensation for increased active power transfer [10]. Each wind turbine interfaces the array via a switchgear that is open when the array system is de-energized and will close when voltage is detected within a specified range, initiating the wind turbine start-up procedure. The reconnection feature is configurable on a per wind turbine basis and can be used to control the portion of wind turbines participating in the black start provision.

OWPPs designed in 2020 are approaching a nominal capacity of up 1.5 GW per project/phase, and the reference OWPP is thus chosen to be 1.4 GW to represent the upper end of the scale. The wind turbines are assumed placed strategically to remove all effects reducing wind inflow velocity, such that the OWPP power curve without network losses equates the sum of the wind turbine power curves. The effective wind speed used for each wind turbine is assumed identical, based on historical data from a representative wind power plant calculated from the average wind speeds of the wind turbines.

The electrical no-load losses of the energized passive equipment of the reference OWPP is estimated via load-flow simulations to equate 6.7 MW, and the generation dependent losses are represented by scaling the OWPP power curve by a static percentage from cut-in to cut-out.

Active equipment such as the IBESS, wind turbines, and dynamic reactive compensation, contributes with additional losses to remain operational. The wind turbine load prior to cut-in depends on many factors such as converter blockage, heating of lubricants and de-humidification of primary components. Historical data was used to estimate the realistic range of consumption when in operation before cut-in, and for start-up. The figure was set to a conservative load of 100 kW per wind turbine. Consequently, the energized wind turbines partaking in black start service provision will act as a significant load on any storage system until generation. Losses associated with generation and absorption of reactive power in the turbines are neglected and the turbine power curve is used as-is without skewing for reactive power.

C. Wind and Power Distribution

Historical wind speed data spanning from late 2011 to late 2017 were used for numerical analysis of rating and capacity dependencies between IBESS and the co-located OWPP when providing black start and frequency services. One-hour data points of the average wind speed was fitted to the classic two parameter Weibull distribution [11] to ensure the validity of the data. The probability density function (PDF) is,

$$F(v,\kappa,\lambda) = \frac{\kappa}{\lambda}\left[\frac{v}{\lambda}\right]^{\kappa-1} e^{-\left(\frac{v}{\lambda}\right)^{\kappa}},$$

The maximum likelihood method was used to fit the data to the distribution resulting in a PDF with scale parameter $\lambda = 11.77$ $[\frac{m}{s}]$, and shape parameter $\kappa = 2.23$, showing skewed right and a small tail. The shape parameter describes the wind behaviour and is usually around 2 or slightly higher for high wind sites, and the scale parameter is representative for an offshore site [12]. Note that given the data originates from measurements at correct altitude, no vertical profile is added. The data can be concluded acceptable as representing a sited OWPP location.

The distribution is shown in the upper half of Figure 1 as an overlay on a histogram of the data, and the cumulative distribution function is shown in the lower half. It is seen that the PDF fits the histogram data and that the error is within acceptable margins.

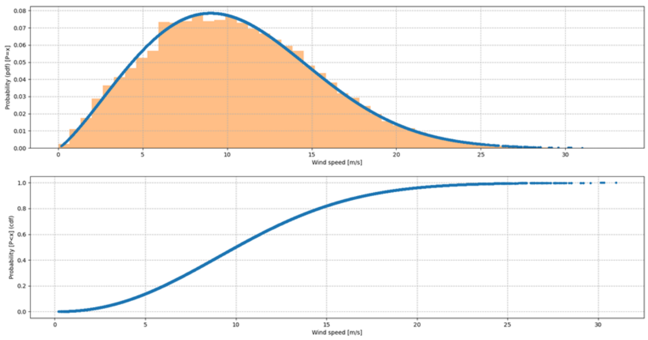

Figure 1: Wind data histogram, PDF and CDF for reference site.

The driving factor for generation is the power curve of the turbines as a function of the wind speed. Applying the power curve of the reference wind turbine to the wind data yields the power distribution including electrical losses. The power distribution does not follow a predefined analytical distribution, and the discrete cumulative distribution is estimated from quantiles. As the wind turbine achieves rated power for a large set of wind speeds, the distribution is clustered at 100% generation, as seen in Figure 2.

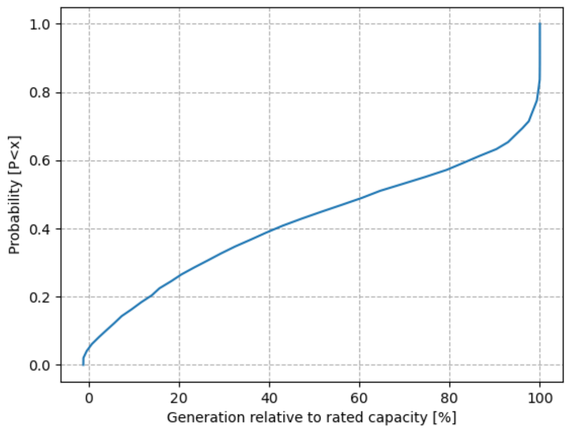

Figure 2: OWPP generation distribution.

Figure 2 provides a graphical representation of the likelihood that an OWPP, or parts of it, relative to its rating can deliver the required power to sustain a black start response post energization of the wind turbines, including electrical losses. The 1.4 GW reference OWPP selected for this paper can for instance deliver 50 MW of active power at the transmission interface point 90.2% of the time which in combination with energy storage is promising. However, this does not consider the cyclic nature of the wind which is important for black start service availability.

D. Scenarios

To capture the worst-case conditions for a battery to perform black start and thereby the design basis, it is assumed that:

i. All black start attempts are performed after having idled with no OWPP generation for 72 hours (maximum resilience requirement);

ii. Losses for all black start attempts are included in the initial energy of the battery, i.e. no generation was possible before last successful attempt;

iii. Battery maximum state of charge (SoC) is 95%, and minimum 5%;

iv. The block-size must be continuously supplied for 10 consecutive hours;

v. Wind turbines have an availability of 97%, WT_{av}. I.e. there is a 3% chance of a turbine not starting.

Assumptions (i) and (ii) infer that no island operation of the OWPP was attempted with energization only successful at the last attempt, just prior to service provision. While the assumptions are harsh, the resulting energy usage is a hard energy requirement for the battery to enable any black start service. The result is a reduced initial state of charge for the chosen battery capacity. However, the effect is easily removed by considering the reduced capacity as the initial capacity. Assumption (v) governs that even though a wind turbine is commanded to start following a black-out, they might be erroneous.

For the scenarios and modelling the wind turbine generation and OWPP losses and generation are assumed linearly scalable with the number of wind turbines selected for participation in black start service. Furthermore, the battery SoC is managed to be at 95% prior to the black-out. The chosen scenarios are:

- Block loading of 20, 30, 40 and 50 MW;
- Battery energy capacities of 10-200 MWh;
- OWPP participation of 1% (14 MW) to 100% (1400 MW),

with durations set as follows:

- Wind turbine start-up time, t_{st} , 5 minutes;
- Network energization time, t_{en} , 30 minutes;
- Resilience duration, t_{sp}, 72 hours.

E. Numerical Model

The goal of the paper is to create a simple numerical model for investigating the black start service provision and dependency between OWPP rating, battery energy capacity and service availability. Given a battery with an initial SoC, S, default 95%, and a battery capacity, C, the initial battery energy, $E(t_{0-})$ is,

$$E(t_{0-}) = CS.$$

The worst-case initial energy consumption of the battery prior to black start service provision, as defined in section D, is the sum of the energy spent energizing the electrical network and the wind turbines,

$$E_{energize=} n_{restarts} WPP_s (WPP_l + WPP_c)(t_{st} + t_{en}),$$

and the energy lost waiting for service activation,

$$E_{resillience} = t_{sp} P_{c,}$$

where WPP_l is the electrical network losses, WPP_c is the turbine own consumption while starting, $n_{restarts}$ is the required number attempts to start the combined system, P_c is the battery own consumption and WPP_s is the percentage of the OWPP partaking in the service. Hence, the energy available to sustain the continuous delivery of block loading post worst-case initial conditions at t_0 is,

$$E(t_0) = E(t_{0-}) - E_{energize} - E_{resillience}.$$

The power balance between generation and consumption at each following time step governs the change in SoC, hence for each point in time the SoC is updated based on the instantaneous power balance at time t,

$$E(t+1) = E(t) + \Delta t \Big(WPP_s \cdot WT_{av} \Big(WPP_g(t) - WPP_l(t) \Big) - (P_c + P_b) \Big),$$

where Δt is the sample time of the wind data, WPP_g is OWPP generation, and P_b is the block loading power delivered for the duration of the service.

A fault in the transmission network can happen at any time, so the black start service availability is defined as the likelihood of delivering the offered service scenario at any point in time. For a wind data set of n data points with requirements and scenarios stated in Section D, the simulation model must consider n identical batteries, where a full black start service duration, i.e., t_d data points, are removed from n to only include full duration results. The black start service is initiated for a battery at each time step with the SoC continuously updated based on the power balance between generation and consumption. If at any point during service provision the SoC of a battery is lower than 5 %, it cannot continue to deliver the service and must disconnect. The failure condition is thus defined as a SoC below 5%. The statistical availability of the black start service is the fraction of successful provisions,

$$n_{success} = n - t_d - n_{faliures},$$

to the number of possible provisions,

$$\%_{avail} = \frac{n_{success}}{n - t_d}.$$

F. *Simulation Results and Interpretation*

This section presents the selected results from simulations for block loadings in the range of 20-50 MW while varying the battery initial capacity, $E(t_{0-})$, and wind turbine participation, WPP_s. Figure 3 shows the resulting availability of the service when the entire OWPP is energized. The load of the wind turbines and electrical network impact the availability to such an extent that no black start service can be provided with a $E(t_{0-})$ less than 40 MWh. However, once the OWPP is energized the availability is increasing almost linearly from 86.3% to 95.3% (20 MW) and 82.0% to 89.8% (50 MW).

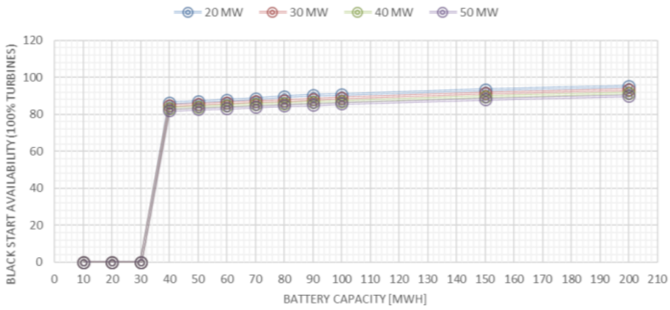

Figure 3: Black start service availability for 100% OWPP participation and block loading of 20-50 MW.

OWPP loading on service availability is investigated by reducing WPP_s to 40% (560 MW). Figure 4 shows the results which follow a similar pattern as for a WPP_s of 100%, with minimum required $E(t_{0-})$ of 20 MWh and an almost linear increase from 82.3% to 96.6% (20 MW) and 73.2% to 87.2% (50 MW).

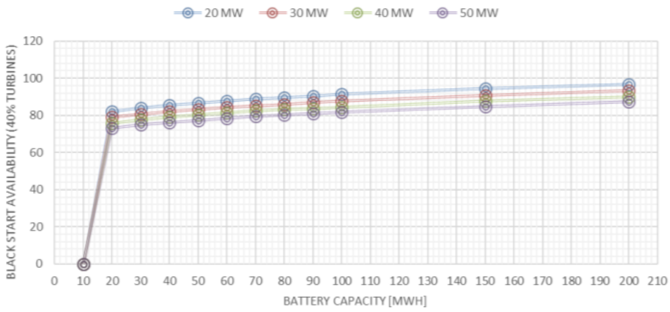

Figure 4: Black start service availability for 40% OWPP participation and block loading of 20-50 MW.

It can be observed that neither scenario result in a service availability of 100%., A maximum of 96.6% is achieved for a 20 MW block loading with a WPP_s of 40%, contrary to the expected WPP_s of 100%. The impact of the OWPP load not only affects the minimum $E(t_{0-})$, but also the achievable availability. WPP_s is reduced to 5% (70 MW) in Figure 5 and the impact of block load power is now very apparent, with a 23% availability difference at 10 MWh, and 37.0% at 200 MWh. While 50 MW block loading with a maximum generation of 70 MW requires operating in high wind conditions for success, the data shows that 5-6 wind turbines of modern rating (12-15 MW) with a 10 MWh battery can achieve 55.7% black start availability for 20 MWh block loading, which is promising for a distributed black start provider strategy.

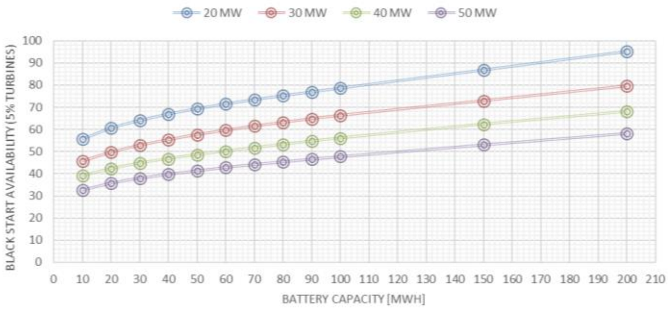

Figure 5: Black start service availability for 5% OWPP participation and block loading of 20-50 MW.

Reducing WPP_s below 3.6% (50 MW) only exaggerates the observed trends and makes the provision of black start increasingly independent on the OWPP, requiring a larger battery capacity. Focusing on the 20 MW block loading as per the minimum requirement, Table 1 summarizes results for select $E(t_{0-})$.

Table 1: Black start service availability for 1-100% OWPP participation and a block loading of 20MW.

WPP_s/ E_{t0-}	20 MWh	30 MWh	40 MWh	60 MWh	80 MWh	100 MWh	150 MWh	200 MWh
1%	0.0	0.0	0.0	0.0	23.5	38.4	60.1	89.0
2.5%	45.8	49.4	52.4	57.8	62.5	67.1	78.4	93.4
5%	60.6	64.1	66.9	71.6	75.3	78.6	86.8	95.2
10%	71.1	74.8	77.0	80.8	83.6	86.2	91.3	96.1
20%	78.5	80.9	82.8	85.5	87.9	89.8	93.6	96.6
40%	82.3	84.1	85.4	87.7	89.6	91.3	94.4	96.6
60%	0.0	84.8	86.1	88.0	89.6	91.4	94.2	96.3
80%	0.0	85.1	86.2	87.7	89.7	91.1	93.9	95.9
100%	0.0	0.0	86.3	87.7	89.5	90.7	93.4	95.3

It is observed that if OWPP energization is possible, increasing the number of participating wind turbines beyond 20% (280 MW) only add 2-4% service availability with lesser gains for larger battery capacities. The lesser gains are caused by the ability of the battery to sustain durations of negative power balance for longer, resulting in a lower required effective generation in the service window. With a 280 MW OWPP, the probability of generating adequate power for sustaining the block load and electrical losses (~22 MW) is 85% once energized according to Figure 2; however the distribution does not capture the underlying cause of the miniscule availably increase, namely the persistency of wind as a resource.

While the load on the battery is insignificant in proportion to the possible generation from the wind turbines, the generation is not utilized due to contiguous very-low wind events that drive the underlying availability. Wind is a persistent and cyclic resource with low-wind windows often having a duration of several hours, such that a black start service provision relies only on the stored energy. Clearly, if no generation from the turbines is available for the entire duration of service provision, the battery must have the capability to provide the needed energy. Increasing the battery capacity will provide resilience against long contiguous low-wind windows netting a gain in availability, but at a heavy cost.

The simulations reveal a set of patterns:

i. A high number of participating turbines can increase energization losses beyond the energy capacity of the battery, making black start impossible to initiate;

ii. Post energization, increasing generation beyond a certain point, e.g., 280 MW for 20 MW block loading, has limited impact on service availability (2-4%), and can have a negative impact due to increased losses;

iii. Increasing battery capacity to sustain a negative power balance for longer has limited effect due to the service availability being dominated by contiguous low wind windows;

iv. Additional generation minimize the effect of the increase in block loading by increasing the minimum required effective wind speed.

While an availability of 100% can be achieved by increasing the battery size to ~300 MWh, the design is economically infeasible, and one must decide on the duration of low-wind events the battery should ride through.

G. Impact of Windows of Low Wind

An impact analysis of long low-wind windows was performed by quantifying sequences in the reference data. Three categories exist with varying degree of impact:

i. Wind speeds below cut-in: Negative power balance- full load on battery.

ii. Wind speeds just above cut-in: Negative power balance - partial load on battery;

iii. Wind speeds above cut-in and generating: Positive power balance, no load on battery.

Data points were sorted and filtered into the relevant categories by wind speed, and the indices were marked if they formed a contagious non-interrupted event. A histogram of the occurrences where the OWPP behaves as a full load is shown in Figure 6. The plot shows that windows with low wind are common, representing approximately 2300 hours over the data period, or ~5.2 %. Windows with a duration of two hours or more represents ~4.8%.

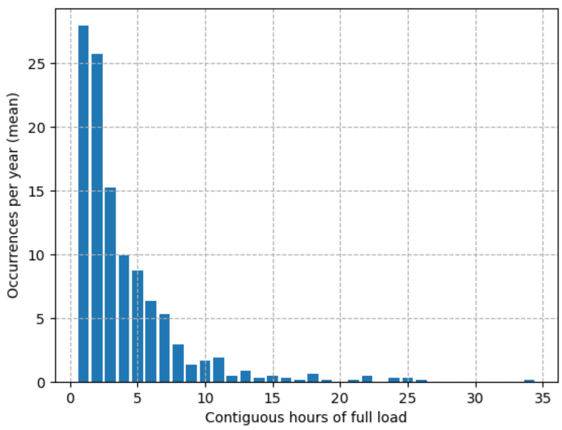

Figure 6: Histogram of full load behavior duration – yearly average.

A histogram of the partial load events is shown in Figure 7, with 2.9% yearly spent in this region, and 50.4% of time in single hour events.

The analysis does not explore the variability, or cyclic, nature of the wind in the vicinity of the windows and clarify if e.g. two 1-hour windows are only separated by a minor increase in wind speed exceeding the threshold and should from a design standpoint be counted as a 3-hour window. This feature is explored by calculating the wind speed standard deviation in the vicinity of the low wind windows. A vicinity is defined as ±5 hours from the center point of the low wind window. Figure 8 shows the persistent nature of wind as the deviation is miniscule - 40% of the cases has standard deviation less than 1 m/s, indicating the incidents in general are part of larger low-wind phenomena.

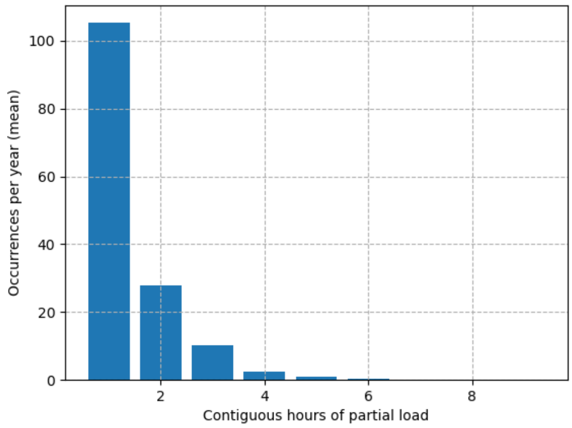

Figure 7: Histogram of partial load behavior duration – yearly average.

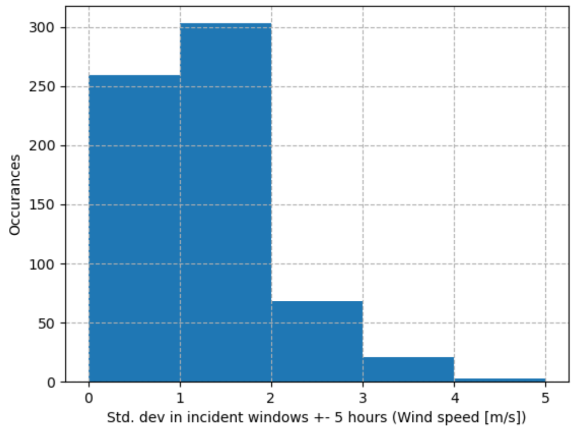

Figure 8: Standard deviation of wind speed ±5 hours from center point of incident.

H. Discussion and sub-conclusion

The simulation results show that the minimum energy and availability requirements of section A *can* be fulfilled for the IBESS associated with an OWPP, but it also begs the question of the economic feasibility of doing so. Within the OWPP, availability can be affected by:

1. Additional wind turbines (generation) to lower the required effective wind speed for positive or neutral power balance, but also increased energization load and the effect of a negative power balance.
2. Larger energy storage to sustain negative power balances and energization load.

Point (1) is subject to diminishing returns and only effective when the block- and OWPP loads are large relative to the possible generation, i.e. it must be ensured that the probability of a positive power balance is adjusted for the individual OWPP in relation to the energy storage size. In the simulation results an increase from 280 MW to 1400 MW only increased the availability from 80.9 to 85.1% for a 20 MW block load. The diminishing returns are further caused by the contiguous low wind windows, constituting a hard limit to the effect of adding more wind turbines if the energy storage size is kept constant. Alleviating methods are to provide power from mixed renewable generation with complementary generation profiles such as solar photovoltaic, tidal and wind power, and the TSO to contract black start services from distributed wind farms geographically spread, reducing risk of concurrent unavailability.

The energy storage is responsible for the initial energization and sustaining negative power balances, which is a function of the generation probability distribution. The simulation results show that the availability is governed by an almost linear (0.097 %/MWh, $R^2 = 0.95$) increase from the base availability provided by the OWPP for the limited data set. Taken to the extreme a change from 20 MWh to 200 MWh, increases the availability from 78.5% to 96.6 %.

This simple initial analysis shows that an OWPP with 280 MW or more of generation capacity associated with an IBESS of 90 MWh, can achieve the minimum technical requirements of 90% availability, but also that a limited battery capacity of 20-30 MWh can achieve 78.5% to 85.1 for the same OWPP. The OWPP will be constructed regardless of black start service provision, but the IBESS has substantial cost implications unless the additional capacity can be utilized to generate secondary revenue streams from other ancillary services, which is a very competitive market. the TSO's must shape their availability requirements wisely as a function of the stochastic properties of the resource of the plant, as not to drive up the total cost of delivering the black start service, e.g. by requiring 70 MWh of IBESS capacity. A consequence of a high total cost of delivery will be that renewables are not prioritized for service provision, as the total cost weighs in at 70% in the commercial assessment. Additionally, a large CAPEX can prohibit smaller developers in providing the black start service at all.

The availability numbers of this analysis are based on a worst-case scenario, and the following alleviating factors must be considered when evaluating the results:

- An OWPP with associated IBESS can operate in electrical island mode prior to service provision, compensating the power used for energization.
- In negative power balance scenarios, wind turbines can be shut down automatically to optimize the power balance.

Additional control features will improve the black start case for OWPP with IBESS.

III. FREQUENCY SUPPORT FROM OFFSHORE WIND POWER PLANTS

It is possible to provide frequency support from OWPPs. However, then the wind turbines would need to operate at a point below the point provided by maximum power point tracking (MPPT) to have enough headroom for both up and down regulation. This results in spilling wind, and thus involves a cost. Therefore, this approach is not attractive.

The intention in this section is to assess the power and energy requirements for frequency support, assuming that an IBESS is installed in relation to an OWPP and assuming that the frequency support, both in terms of inertia emulation and fast frequency droop control, is provided from the IBESS instead of the OWPP.

A. Frequency Support Requirements

The requirements for providing new frequency support services as provided by battery energy storage, are still developing. In order to see how inertia emulation and fast frequency droop control may meet currently discussed frequency support services, inspiration is based on published material originating from Great Britain.

NGESO has in [9] specified a fast frequency response service referred to as Dynamic Containment, summarized in Figure 9.

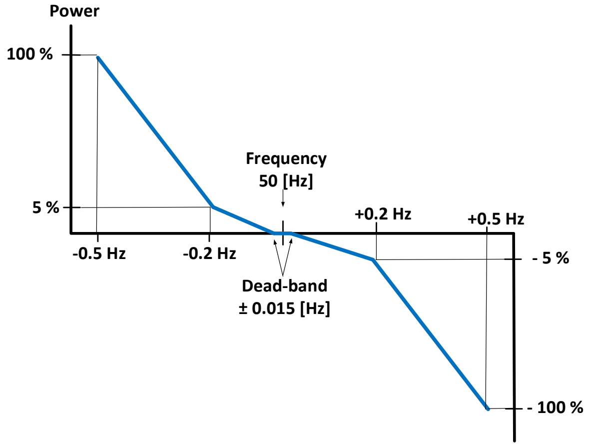

Figure 9: Dynamic Containment from [9].

The y-axis corresponds to per cent of contracted power and the x-axis indicates frequency deviation from 50 Hz. There is currently a unit cap on 50 MW. We can note that:

- Dead-band delivery is 0% (±0.015 Hz);
- Small linear delivery is required between 0.015 Hz and 0.2 Hz, to a maximum of 5% at 0.2 Hz;
- Knee point activation at ±0.2 Hz is 5%;
- Full delivery ±0.5Hz is 100%;
- Linear delivery knee point (0.2 Hz) and full activation (0.5 Hz);
- Full delivery required in at most 1 s but no faster than 0.5 s.

In an accompanying document, [14], it is indicated that the duration of the power injection/extraction should be 15 minutes at full power, or equivalently at lower power, e.g. 50% for 30 minutes.

In [9] NGESO indicates that they are looking to create markets for inertia, but further specifications have not yet been found. In this section it is assumed that the same inertia equivalent, i.e. 800 MVA.s, as required in Section II.A for black start, would be of interest also in the general case.

B. Control Scheme for Frequency Regulation

As in particular OWPPs frequently are connected at weak points of power systems, it has in this work been decided to use a grid-forming control scheme, more precisely a variant based on [14], capable of providing both fast frequency support and inertia emulating control. For the purpose of facilitating a discussion on required power and energy ratings of IBESS, the control scheme for active power is redrawn as shown in Figure 10.

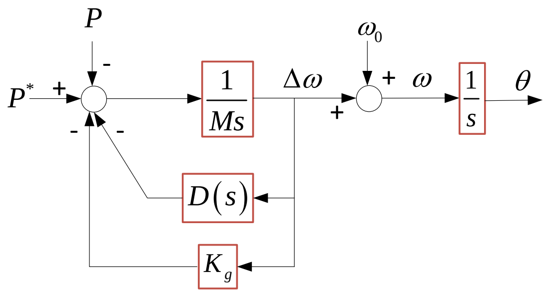

Figure 10: Synchronous generator emulation with damping and frequency droop

Thus, the active power loop emulates a synchronous generator, with damping and frequency droop. This can be written out as,

$$sM\Delta\omega = P^* - P - K_g\Delta\omega - D(s)\Delta\omega \ \text{[W]},$$

where,

$$M = \frac{2HS_{Bm}}{\omega_0}, \quad s = \frac{d}{dt},$$

and H [s] is the inertia, S_{Bm} [VA] is the rated power, ω_0 [rad/s] is the nominal electrical speed. Further, P^* [W] is the active power reference, P [W] is the measured injected active power, K_g [Ws/rad] is the droop constant, $\Delta\omega$ [rad/s] is the deviation from nominal speed and $D(s)$ provides damping

$$D(s) = K_D\left(\frac{s}{s+\alpha_f}\right),$$

where K_D is a virtual damping constant applied to the high-pass filtered speed deviation.

C. Storage Unit Active Power and Energy Requirements

The power requirements on IBESS, when performing inertia emulation, will depend on both the inertia constant it is delivering, and on the Rate of Change of Frequency (ROCOF) at disturbances [15,16,17]. In the following, the under-frequency case will be considered, where e.g. a production unit has tripped causing a drop in frequency. The corresponding over-frequency case following e.g. a trip of a major load is similar.

If the *j*:th generator is tripped, the initial system ROCOF can be written,

$$\left.\frac{df_{sys}}{dt}\right|_{t=t_0^+} = -\frac{f_0}{2\left(S_{m,sys}H_{sys} - S_{Bm,j}H_j\right)}P_{m,j}(t_0^-) \ \text{[Hz/s]},$$

where $P_{m,j}(t_0^-)$ [W] is the mechanical (turbine) power of the *j*:th generator prior to the trip. Further, with n being the number of synchronous machines in the system, the total rated apparent power and inertia in the system become

$$S_{m,sys} = \sum_{i=1}^{n} S_{Bm,i} \ \text{[VA]}, \quad H_{sys} = \frac{1}{S_{m,sys}}\sum_{i=1}^{n} H_i S_{Bm,i} \ \text{[s]}.$$

The kinetic energy stored in the all rotating masses of synchronous machines in the system can now be written,

$$W_{K,sys} = S_{m,sys}H_{sys} \ \text{[Ws]}.$$

Thus, it follows that the less kinetic energy in the system, the higher system ROCOF in absolute terms. The critical trip of a production unit is often taken to be the largest production unit in the system (assuming an N-1 security philosophy). Let machine j be the largest production unit such that the largest system ROCOF can be written,

$$ROCOF^{max} = \frac{f_0}{2(S_{m,sys}H_{sys} - S_{Bm,j}H_j)} P_{m,j}(t_0^-) \ \text{[Hz/s]}.$$

ROCOF management, in the sense of making sure that enough rotating energy is connected in the system, becomes a central task in a system with large amounts of converter connected renewable energy sources. Figure 11 illustrates the qualitative behavior of the system frequency for the under-frequency case. Due to primary frequency control (frequency droop) collectively performed by several units in the system, the system ROCOF is largest immediately following the trip, and is then reduced such that it is zero at the nadir.

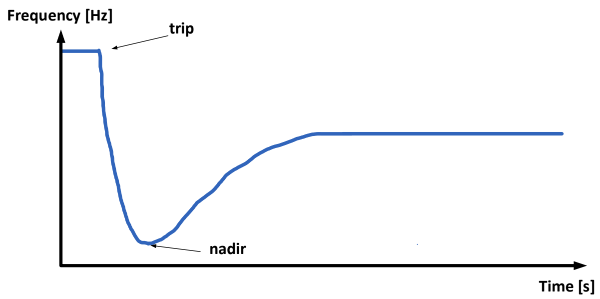

Figure 11: Frequency containment process (under-frequency case).

Different TSOs report that the systems will run into difficulties (load shedding and generation trips) at different levels of ROCOF. In UK it is reported that some non-synchronous generation will trip at 0.125 Hz/s and all non-synchronous generation will trip at 1Hz/s, however South Australia for instance reports ROCOF up to 3 Hz/s, [17].

Assume that generator $k \neq j$ is the synchronous machine emulating IBESS. If the droop is removed for the time being, by setting $K_g = 0$, and the damping for simplicity is ignored, by setting also $K_D = 0$, the relation,

$$\frac{2H_k S_{Bm,k}}{f_0}\left(\frac{\mathrm{df_k}}{\mathrm{dt}}\right) = P_k^* - P_k,$$

is obtained for the IBESS. For a system in synchronism, the local machine frequencies will oscillate around the system frequency in the transients following the trip. The individual deviations from the system frequency will depend on the actual disturbance, but for the sake of obtaining an estimation of the required power, the local frequency will here be approximated by using the system frequency. If in addition the active power reference is set to $P_k^* = 0$, the maximum power required for inertia emulation is obtained as

$$P_k^{max} = -\frac{2H_k S_{Bm,k}}{f_0}\left(\frac{\mathrm{df_{sys}}}{\mathrm{dt}}\right) = \frac{2H_k S_{Bm,k}}{f_0} ROCOF^{max}.$$

Thus, the required active power is dependent on both the system characteristics in terms of $ROCOF^{max}$, and the agreed upon equivalent inertia $H_k S_{Bm,k}$. Figure 12 shows the required active power as a function of maximum ROCOF for a few different equivalent inertias.

It can be concluded that for instance a 50 MW IBESS has a good chance of providing 800 MVA.s equivalent inertia in a system with a $ROCOF^{max} = 1$ [Hz/s], without hitting limit. It should be remembered that the local ROCOF is likely to deviate from the system ROCOF to some extent.

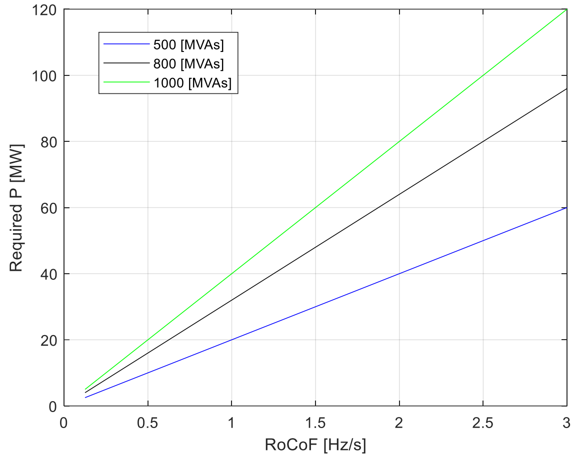

Figure 12: Required active power versus maximum ROCOF for different equivalent inertias.

In order to estimate the kinetic energy required for inertia emulation, the rated kinetic energy stored in turbine-generator string of unit i is considered,

$$W_{kR,i} = \frac{1}{2} J_i \omega_{mR,i}^2 = H_i S_{Bm,i},$$

where J_i [Ws] is the moment of inertia and $\omega_{mR,i}$ [rad/s] is the rated mechanical speed. Further, let $\omega_{m,i}$ [rad/s] be the mechanical speed of the rotor, and p_f be the number of poles of the generator, then

$$\frac{\omega_{m,i}}{\omega_{Rm,i}} = \frac{\omega_i/p_f}{\omega_0/p_f} = \frac{\omega_i}{\omega_0} = \frac{f_i}{f_0},$$

If the generator speed is changed from $\omega_{mR,i}$ [rad/s] to $\omega_{m,i}$ [rad/s], the change in kinetic energy becomes

$$\Delta W_{k,i} = \frac{J_i}{2}(\omega_{mR,i}^2 - \omega_{m,i}^2) = H_i S_{Bm,i}\left(1 - \frac{f_i^2}{\mathrm{f}_0^2}\right) \ \text{[Ws]},$$

Referring to the under-frequency case in Figure 11 and assuming nominal frequency prior to the trip, the energy required will depend on the system character in terms of the lowest expected frequency nadir, f_{min} [Hz], and the agreed upon equivalent inertia $H_k S_{Bm,k}$ for IBESS. Thus, the energy required to emulate an inertia response becomes

$$E_k = H_k S_{Bm,k}\left(1 - \frac{f_{min}^2}{\mathrm{f}_0^2}\right) \ \text{[Ws]}.$$

Figure 13 shows the energy required versus expected minimum frequency nadir for the under-frequency case and for a few different equivalent inertias. It can be concluded that the energy required for inertia emulation is quite limited. A corresponding estimation for the over-frequency case is very similar.

The estimation of required power and energy for fast frequency support in the form of Dynamic Containment as discussed in Section III.A seems straight forward. If it is assumed that the contracted power is ±50 MW, the required energy for 15 minutes obviously becomes ±12.5 MWh.

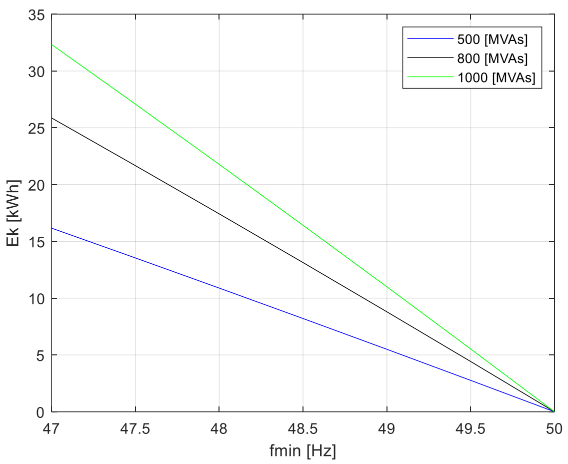

Figure 13: Required energy versus frequency nadir.

A tentatively promising circumstance with the combination of inertia emulation and fast frequency support is that they to some extent complement each other in terms of usage of the active power range. Whereas the inertial response is expected to require most active power immediately following the trip, and thereafter reduce to zero at the nadir, the frequency droop control requires zero power immediately after the trip and increases to be at the maximum at the nadir. Thus, there are possibilities to stack these two services, utilizing at least partially the same active power range. Whether this would be in line with the specifications set forward in the system service market is still uncertain.

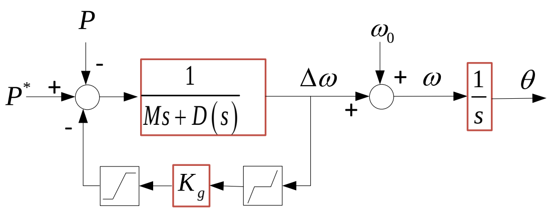

Figure 14: Conceptual implementation of Dynamic Containment

Figure 14 conceptually indicates a feedback loop establishing the Dynamic Containment service, with limiter for maximum power and a dead band around zero frequency deviation. The two slopes in Figure 9 could be establish through gain scheduling of K_g.

D. Discussion

The active power requirement for inertia emulation is partly driven by the maximum system ROCOF, which needs to be specified by the TSO for rating purposes. The energy required for inertia emulation is however small, at least with the inertia equivalents assumed here. Providing fast frequency support through droop control is straight forward, although it may require substantial energy.

IV. Conclusions

The size of the battery energy storage for IBESS utilizing the black start ancillary service depends heavily on the availability requirement to perform the black start. The rated power of the investigated OWPP is 1.4 GW. An availability of 80% is achieved with 30 MWh with only 20% (280 MW) of turbines in operation. For an availability of 90%, an 80-90 MWh storage and 40% of the turbines need to be in operation. Finally, for an availability of 95% the storage needs to be 200 MWh and all turbines need to be in operation. The results show that small OWPP with associated battery systems can deliver black start services with a high availability (>80%). Hence, the design of market mechanisms and selected technical abilities are vital in ensuring adequate competition and enabling renewable resources to participate in the market. The TSO should aim for a distributed service from smaller OWPPs with less strict requirements on availability, to gain resilience though scale – and add incentives to provide black start from mixed generation plants.

The needed power for the ancillary service of virtual inertia depends on the ROCOF and the time constant of the virtual inertia. The energy needed for the virtual inertia depends on the frequency deviation to the nominal frequency and the inertia time constant. The energy is only a fraction of what is needed for the black start functionality.

Acknowledgment

The project was financed by Innovation Fund Denmark with grant number 8055-00074B.

References

[1] P. Kundur, "Power system stability and control," McGraw-Hill, New York, 1994.

[2] S. Chaudhary et al., "Challenges in Integration of MMC STATCOM with Battery Energy Storage for Wind Power Plants," Wind Integration Workshop, Dublin, Ireland, October 2019.

[3] S. Chaudhary et al., "Techno-economic Feasibility of a STATCOM with Battery Energy Storage for the Offshore Wind Power Plants," CIGRE Symposium Aalborg, Denmark, June 2019.

[4] Daniela Pagnani, Łukasz Kocewiak, Jesper Hjerrild, Frede Blaabjerg, Claus Leth Bak, "Challenges and Possible Solutions in Integrating Black Start into Offshore Wind Farms," in Proc. The 19th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as Transmission Networks for Offshore Wind Farms, Energynautics GmbH, 11-12 November 2020, [Accepted] 28 August 2020.

[5] Daniela Pagnani, Lukasz Kocewiak, Jesper Hjerrild, Frede Blaabjerg, Claus Leth Bak, "Overview of Black Start Provision by Offshore Wind Farms," in Proc. of IECON 2020: 46th Annual Conference of the IEEE Industrial Electronics Society, 18-21 October 2020.

[6] National Grid ESO, "Technical Requirements & Assessment Criteria", 2019.

[7] National Grid, "Black Start Strategy", 3rd of August 2017.

[8] V. Knap, S. K. Chaudhary, D. Stroe, M. Świerczyński, B. Craciun, R. Teodorescu, "Sizing of an Energy Storage System for Grid Inertial Response and Primary Frequency Reserve," in IEEE Transactions on Power Systems, vol. 31, no. 5, pp. 3447-3456, September 2016.

[9] Daniela Pagnani, Frede Blaabjerg, Claus Leth Bak, Filipe Miguel Faria da Silva, Łukasz H. Kocewiak, Jesper Hjerrild, "Offshore Wind Farm Black Start Service Integration: Review and Outlook of Ongoing Research," Energies, [Submitted].

[10] S.K. Chaudhary, A.F. Cupertino, R. Teodorescu, J.R. Svensson, "Benchmarking of Modular Multilevel Converter Topologies for ES-STATCOM Realization," Energies 2020, 13, 3384.

[11] K. Adepoju, O. Shittu "On the Exponentiated Weibull Distribution for Modeling Wind Speed in South Western Nigeria", May, 2014, Journal of modern applied statistical methods: JMASM.

[12] F. Mahmood, A. Resen, A. Khamees, Energy Reports 6 (2020), EURACA, Elsevier.

[13] National Grid ESO, Dynamic Containment, January 2020.

[14] L. Harnefors, M. Hinkkanen, U. Riaz, F.M.M. Rahman, and L. Zhang, "Robust Analytic design of Power-Synchronization Control," IEEE Trans. on Ind Electronics, Vol 66, No. 8, August 2019.

[15] Ujjwol Tamrakar, Dipesh Shrestha, Manisha Maharjan, Bishnu P. Bhattarai, "*Virtual Inertia: Current Trends and Future Directions*," Applied Sciences, MDPI, 26 June 2017.

[16] Inertia: Basic Concepts and Impacts on the ERCOT Grid, 2018.

[17] PPA Energy, "Rate of Change of Frequency (ROCOF) Review of TSO and Generator Submissions Final Report," May 2013, [Online] https://www.cru.ie/wp-content/uploads/2013/07/cer13143-a-ppa-tnei-rocof-final-report.pdf.

[18] ENTSO-E, "Rate of Change of Frequency (RoCoF) withstand capability ENTSO-E guidance document for national implementation for network codes on grid connection," [Online] https://docstore.entsoe.eu/Documents/Network%20codes%20documents/NC%20RfG/IGD_RoCoF_withstand_capability_final.pdf.

[19] Inertia: Basic Concepts and Impacts on the ERCOT Grid, 2018.