Optimal Sizing of Battery Energy Storage to Enable Offshore Wind Farm Black Start Operation

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***Abstract*—The goal of transitioning toward 100% renewable energy sources (RES) poses serious challenges to the black start service in electrical power systems. In the instance of a blackout, black start units must restore the power. Conventional black start sources are often taken out of operation to accommodate a larger share of RES and this jeopardises the resiliency of the grid. To replace conventional black start units, offshore wind farms (OWFs) can become future black start providers. However, a black start unit must meet stringent technical requirements, and due to the variable power output of OWFs, it may be challenging to meet these requirements without external support. Therefore, battery energy storage systems (BESSs) are a promising solution to support OWFs to satisfy black start requirements.**

In this paper, a probabilistic method is applied to determine the optimal BESS power output to support the OWF during black start operation. The considered black start technical requirements are taken from the British Transmission System Operator (TSO). The wind generation behavior is approximated with a Weibull distribution, and BESS power output is estimated considering a worst-case scenario logic. Finally, results are validated with a series of load-flow simulations to verify the time series generation of an OWF. The analysis conducted shows that the required power output from a BESS is dependent mainly on the size of the OWF and the availability requirement dictated by the TSO.

***Index Terms*—black start, offshore wind farm, battery energy storage system, technical requirements, probabilistic method.**

I. INTRODUCTION

To reach net-zero emission in 2050 as per the Paris Agreement, renewable energy sources (RES) are being installed, whereas conventional plants decommissioned. Therefore, the overall behavior of the power system is becoming more unpredictable, increasing the risk of blackout in the power system [2]. Once a blackout occurs, the power system restoration has three steps: black start, network reconfiguration, and load restoration [3]. Particularly, the black start is the process to restore the electrical network from the shutdown to start supplying power without relying on the external grid. Nowadays, conventional power plants (e.g., thermal power plants) act as black start providers. However, the future RES-based power system will show a lack of black start providers, leading to a weaker resiliency after a blackout.

To deal with this problem, RES can take a major role in providing black start services, particularly large offshore wind farms (OWFs). Nowadays, there are no black start units from RES, but the large capacity and the short start-up time of OWFs seems an attractive solution [2], [4], [5]. However, OWFs may need extra help to satisfy all black start technical requirements defined by transmission system operators (TSOs) [1], [2]. In fact, wind power fluctuations caused by wind speed variability result in serious concern about the reliability and satisfactory operation for black start capability. One solution is to integrate a battery energy storage system (BESS) into the OWF. From that perspective, determining the optimal size of BESS to enable the wind farm to operate as a black start source is necessary from both economic and technical points of view [1], [3], [7].

Some research on the topic of BESS sizing with OWFs to provide black start service has already been developed. In the literature, the joint probability distribution and asymmetric copula function were used to size the energy storage for the wind farm to be a black start unit [7]. The energy storage services in this study deal with frequency stability during the energization process and smoothing the power output during the starting up generator process. The optimization problem formulation is based on the chance constraint programming model aiming to minimize the capital cost. Reference [3] used the same procedure, but the size of energy storage was mainly concerned in the last stage of the black start process (smoothing the power output during the start-up generator process). However, these sources do not consider the main technical requirements provided by TSOs such as the availability requirement for at least 90 % of the time and supplying power to a minimum 20 MW block load as per the British

TSO [16].

This paper focuses on optimizing the BESS inverter size to enable the black start operation of an OWF satisfying the availability and block load requirements provided by the British TSO, i.e., National Grid Electricity System Operator (NGESO). A probability method is proposed. A Weibull distribution is used to represent the wind power behavior and estimate the power production of the OWF in the worst case scenario.

The rest of this article is organized as follows. Section II reports the state-of-the-art review, the technical requirements for black start providers, black start functionality by OWF with BESS, and the most common BESS sizing methods for black start service. Then, Section III presents the optimization methodology and the sizing algorithm. Section IV collects results and simulations of the investigation. Finally, Section V summarizes conclusions and future work.

II. STATE-OF-THE-ART REVIEW

A. Technical Requirements for Black Start

The future integration of RES as black start units is gaining attention worldwide. However, to become a black start provider, an OWF must be able to meet stringent technical requirements. Currently, these requirements are applied to conventional units and not to RES. However, some TSOs, such as the British TSO NGESO, extended the set of requirements to new possible RES [1].

Some of the main requirements are here listed:

- **Service availability:** the black start source must provide the black start service for a minimum time determined by TSOs. NGESO sets the minimum required time at 90 % of the year [5], [6], [15].

  The availability problem is a severe concern for the offshore black start source, as their power output highly depends on the wind variability. This problem can be solved if OWF are equipped with BESS.
- **Block loading capability:** The ability to accept continuous power demand. For black start the power demand could be the required power need it to start up a generator unit. NGESO sets the minimum block load to 20 MW [6].
- **Resiliency of supply:** This is defined as the ability to provide power continuously at the output required. Based on NGESO, this requirement can be classified into two type as follow [5]:
  1) The black start resiliency of supply of black start units for $\geq$ 10 h, meaning the ability to deliver continuous power to a block load for at least 10 hours.
  2) The black start resiliency of supply of auxiliary units for $\geq$ 72 h, meaning the ability to deliver or support continuously the output required for the black start service for at least 72 hours [6].

The requirements presented above are the one of main importance for the current investigation. The reader can find the whole list of black start technical requirements by NGESO in Table I.

TABLE I
List of black start requirements by National Grid Electricity System Operator [2].

Category	**Requirement**
Self-start	Yes
Time to connect	$\leq$ 2 h
Service availability	$\geq$ 90 %
Voltage control	$\pm$10 %
Frequency control	47.5 Hz - 52 Hz
Block load	20 MW
black start service resiliency of supply	$\geq$ 10 h
black start auxiliary unit resiliency of supply	$\geq$ 72 h
Reactive capability	$\geq$ 100 MVAr leading
Inertia value	$\geq$ 800 MVA.s.
Sequential start-ups	$\geq$ 3
Short-circuit level	$240\ \frac{MVA}{\sqrt{3}U} KA\ (t < 80ms), and\ 10\ \frac{MVA}{\sqrt{3}U}$

In this paper, the concern of the black start requirements are mostly on the block loading capability, service availability and resilience of supply.

B. Offshore Wind Farm Black Start Strategy with BESS

The functionality of the black start phase using wind farm and BESS can be divided into four steps as follow [3], [7], [8]:

1) Wind farm starting up.
2) Energizing of transformers and transmission lines.
3) Starting up the large ancillary machine.
4) Starting up generator unit.

The energizing of the transformers and transmission lines from no load to full load will cause an over-voltage. Therefore, this step should be controlled by using a reactive power compensation device to prevent the wind turbines from tripping off.

The BESS sizing problem to enable OWF to be a black start source is formulated as three sub-problems as follows [3], [7]:

- **Sub-problem 1:** it deals with wind farm starting up. The wind turbines need external power sources to start up due to a lack of self-starting ability. Thus, BESS can work as a self-start unit and provide the active power load that the OWF needs to start.
- **Sub-problem 2:** it deals with starting up a large ancillary machine. In conventional power plants, the ancillary machines are usually double squirrel induction machines which will cause a frequency and voltage deviation when starting up. The voltage drop can be handled with a reactive power compensation device such as a VAR device. The OWF equipped with BESS can recover the system frequency very fast and thus ensure frequency stability during black start process.
- **Sub-problem 3:** it deals with starting up the generator unit. The conventional power plant needs a steady power to start up from the shutdown state in order to begin ready to provide power again. The BESS can operate as an energy buffer that smooths the power output of the OWF to provide steady power to start the generator unit.

The optimal size problem of BESS can be represented as follows:

$$P_{BESS} = max\left\{P_1, P_2, P_3\right\} \tag{1}$$

$$E_{BESS} = E_1 + E_2 + E_3 \tag{2}$$

where :
P_1 , P_2 and P_3 are the power needed for sub-problem 1,2 and 3.
E_1, E_2 and E_3 are the capacity needed for sub-problem 1,2 and 3.

According to [3] and [7], the required BESS power size for sub-problem 1 and 2 is smaller than the power size for sub-problem 3. The same applies for the capacity need, thus the capacity size for sub-problem 1 and 2 is smaller than the capacity size for sub-problem 3. Therefore, sizing the BESS for the wind farm to be a black start unit can be represented by the capacity and power needed for sub-problem 3.

In general, to apply the black start service problem to BESS sizing, the key features to consider are [3], [7]:

1) The black start source should provide steady power output for a certain period of time to block load.
2) Maintain system frequency as well as voltage stability.

The frequency and voltage drop problems occur when starting up the wind turbines and large ancillary machines while smoothing the power output from the wind farm problem is necessary for providing steady-state power output for the block load process. After providing enough power to restore the frequency and voltage, the system is ready to provide stable power to start up a non-black start generator unit.

C. BESS Sizing Methods

Several methods are used to find the ideal size of the BESS. The optimal size could be found through the usage of an economic indicator when the size minimizes the total investment and operating costs, or a technical indicator when the size satisfies minimum technical requirements regardless of the cost of the BESS [9], [10]. An overview about the different methods and techniques to determine the optimal size of BESS is taken from [9], and here summarized:

1) **Probabilistic methods**: They are commonly used because of their simplicity when applied to sizing BESS with uncertainty, such as the problem related to RES. One of the probabilistic methods is to estimate the historical data of the RES with one of the typical distributions (for example the Weibull distribution), and generate a large number of scenarios (synthesis data) according to the statistical behavior of random variables. Generating a large number of synthesis scenarios have two advantages. The first advantage is to reduce the errors caused by inaccurate forecasting. The second advantage is that the scenarios generated have an equal probability distribution. The BESS size can be estimated directly from the synthesis scenarios or use the scenarios as input to another method. For example, reference [10] uses a probabilistic method to generate scenarios and use them as input for a stochastic optimization problem.
2) **Analytical methods**: They are used in a wide range of services in power systems. They are based on iteratively analyzing and evaluating the performance of the power system using input data and parameters. The success criteria for sizing the BESS in these methods are economic indicators such as net present value (NPV), or technical indicators such as frequency or voltage of the system.
   For example, reference [11] uses the analytical method for frequency control of micro-grid and the optimal size of the BESS is achieved by the balance between generation and demand.
3) **Mathematical optimization methods**: Applications of these methods are mostly in the electricity markets - such as day ahead or intra-day markets - to optimize the daily performance of the system.
   The BESS size can be formulated as a linear problem (LP) or mixed integer linear problem (MILP) with an objective function minimizing the total cost of the battery or maximizing the total profit of the system subject to some technical constraints. These problems need a professional software consisting of optimization tools so to find the optimal solution with respect to the problem constraints [12].
4) **Heuristic methods**: They contain all methods inspired from the nurture such as Particle Swarm optimization (PSO) method or Genetic algorithm (GA) [11].

Being the BS problem subject to uncertainty due to OWF production, the probabilistic method is the preferred one in the current investigation.

III. BESS OPTIMIZATION METHODOLOGY

This section applies one-by-one all steps of the probabilistic method to estimate the BESS power rating to provide black start support. This method requires a cumulative wind generation data as input, so an historical offshore wind generation. For this investigation, the wind farm generation is represented by the UK offshore wind farm capacity factor, expressed in pu [14]. The chosen capacity factor is the ratio between the overall Great Britain offshore wind production divided by the UK offshore wind power capability [16]. Therefore, the collected capacity factor must be multiplied by the rated capacity of the represented OWF (in MW) to calculate the wind power production. Finally, the calculated wind power production is subtracted by the chosen block load to estimate the required BESS power size. In conclusion, the worst-case generation for a wind farm is of crucial importance to estimate the required BESS power size for BS support.

A. Cumulative Data Analysis

The cumulative generation data are first analyzed, then estimated by the statistical distribution that fits the variation of the wind generation profile. In this paper, the Weibull distribution has been used to represent the behavior of the wind generation data. After that, the synthesis data was generated.

Finally, the boundary for the upper 90 % of wind generation values are determined for both historical and synthesis data. In other word , the probability of getting less than this value is 10 % (worst-case scenario), or the confidence level of getting higher than this value is 90 %. In this case, the method guarantees the availability of supplying power to the block load process 90 % of the time. The fluctuation caused by the wind results in a variable wind generation profile, as reported in figure 1. In order to deal with the generation profile mathematically and calculate the confidence level for the power generated in the worst-case scenario, it is necessary to represent the behavior of wind energy statistically using one of the statistic distributions. The Weibull distribution is usually used when dealing with wind speed variation. However, the Weibull distribution in used here since it was the most suiting for the historical wind generation data acquired from [14].

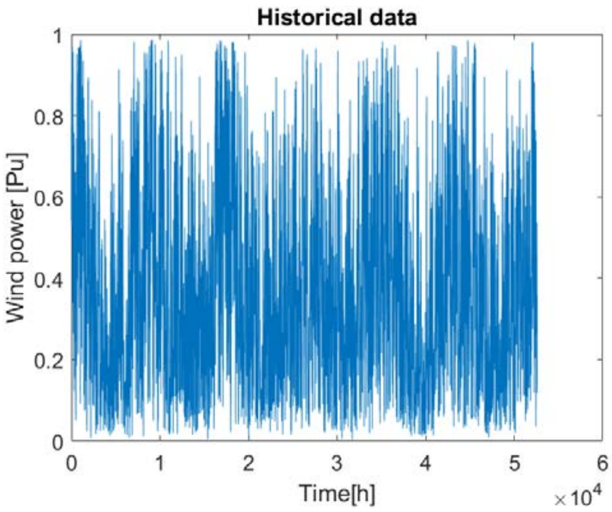

Fig. 1. Historical offshore wind generation capacity factor in Great Britain from 2014 to 2019.

In order to evaluate the estimated parameters that fit the Weibull distribution, the PDF, CDF, and ICDF are calculated.

The PDF for Weibull distribution is mathematically described as [15]:

$$w(x,a,b) = \frac{b}{a}\left(\frac{x}{a}\right)^{b-1} e^{-(x/a)^b} \tag{3}$$

where :

- a is the scale parameter, in this case equal to 0.415 pu.
- b is the shape parameter, in this case equal to 1.6.
- x is the data set or the wind generation in pu.

Figure 2 shows the PDF curve for the historical wind generation data under investigation. It can be seen that the Weibull distribution gives a good estimation about the given wind farm generation data.

The PDF returns the density of probability for each value estimated x (wind generation in pu), thus to evaluate the probability for the wind generation parameters, the CDF and its inverse ICDF are utilized.

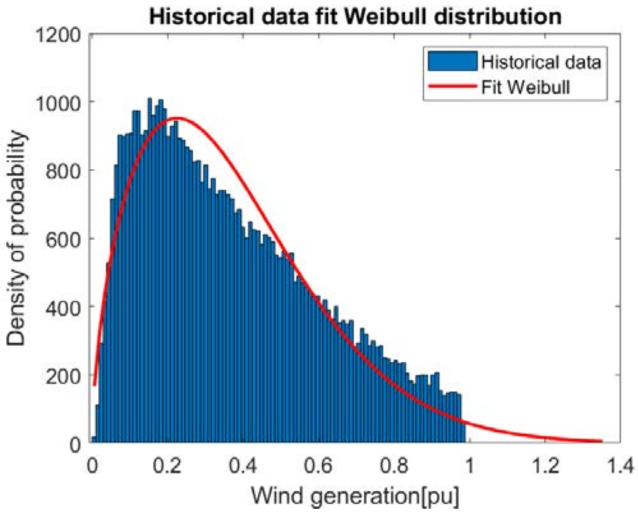

Fig. 2. Data fitting by Weibull distribution.

The CDF for Weibull distribution is mathematically described as [15]:

$$p(x,a,b) = \int_0^x b a^{-b} t^{b-1} e^{-\left(\frac{x}{b}\right)^b} dt = 1 - e^{-\left(\frac{x}{b}\right)^b} \tag{4}$$

The resulting p is the probability that a single observation from the Weibull distribution - with parameters a and b - falls in the interval [0 x]. Figure 3 shows how the CDF curve for the considered historical data fits the Weibull CDF curve. The cumulative probability of each estimated wind generation data is represented in the Y-axis ranging from 0 to 1 and the x-axis represents the wind generation in pu. Therefore, on the one hand, the input of the CDF are the Weibull distribution parameters (a and b) and the wind generation in pu. On the other hand, the output is the probability of observing a wind generation value lower or equal than the given input x.

The confidence level for any scenario is calculated using the CDF curve for a given generation value as follows:

$$confidence(x) = 1 - p = 1 - CDF(x) \tag{5}$$

As previously reported, the CDF returns the probability using the wind generation as an input. Therefore, in order to estimate the wind generation for a specific confidence level, the ICDF for the Weibull distribution is needed. The mathematical equation for the ICDF for the Weibull distribution is [15]:

$$x = F^{-1}(p,a,b) = -a[ln(1-p)]^{1/b} \tag{6}$$

Figure 4 shows that the ICDF curve for the Weibull distribution fits to the one of the historical data.

In conclusion, the worst-case generation value is detected by using the ICDF curve for a given probability:

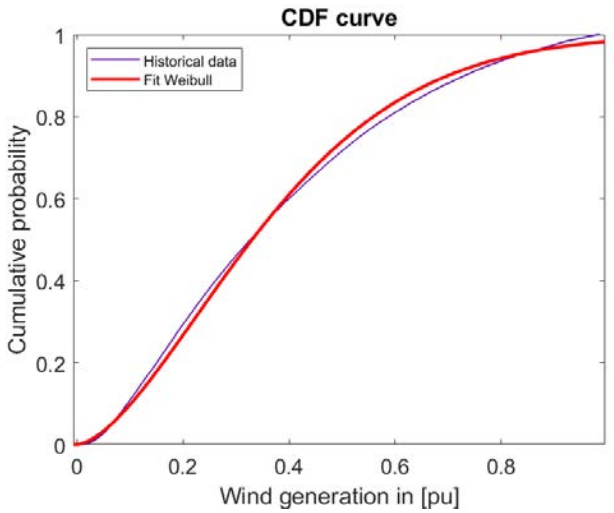

Fig. 3. Cumulative distribution function curves: historical data vs Weibull distribution.

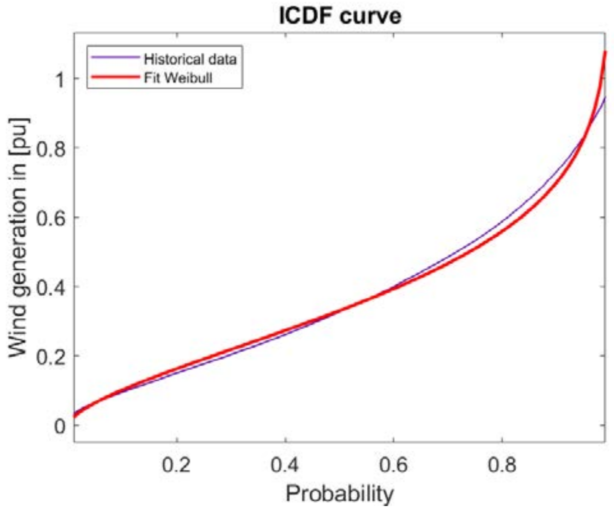

Fig. 4. Inverse cumulative distribution function curves: historical data vs Weibull distribution.

$$ICDF(p) = x \tag{7}$$

B. Synthesis Data Generation

The synthesis data are generated using the Weibull's parameters a and b, which characterize the historical data distribution shape and scale. The function Random(Pd,S,N) in MATLAB is utilized to generate the synthesis data, which returns a random variate from probability distribution object Pd. The number of scenarios S means how many times the sample data will be iterated. Moreover, the sample data size N is the number of synthesis wind generation values. Therefore, the input of the random function are the Weibull distribution characteristics a and b, the number of synthesis data N, and the number of scenarios S. The resulting variable are wind power generation data that fit the Weibull distribution.

The number of scenarios plays an essential role. In fact, more scenario will create a generation profile that fits better to the distribution, and thus the error when estimating the worst-case value will be smaller.

Figure 5 shows the effect of the number of scenarios on the shape of the probability distribution of the data. It can be seen that 100 and 1000 scenarios data fit to the Weibull distribution better than 1 or 10 scenarios. The 100 and 1000 scenarios have approximately the same shapes. Therefore, the number of scenarios N has been chosen is equal to 100.

Figure 6 shows the CDF and ICDF curves for the synthesis data generation, compared to the CDF and ICDF curves for the Weibull distribution. As expected, the errors are smaller compared to the historical data.

C. BESS Size Estimation Algorithm

Figure 7 shows the flowchart of the method applied to estimate the production of the wind farm and the BESS size in the worst-case scenario. It starts by estimating the historical data by Weibull distribution to capture the maximum likelihood values of the wind generation. The synthesis data are then generated and fitted to the Weibull distribution to validate the data estimation and reduce the errors. After the data estimation, the boundary value at 90% confidence level has be calculated, and thus BESS size for the worst-case scenario has been executed.

It is worth noticing that this method might be applied for different distributions, for example, kernel or exponential distribution. It depends on how the time-series data are distributed over a specific time.

D. BESS Power Rating Estimation

The BESS power rating is calculated by taking the difference between the block load demand and the estimated worst-case power generation.

The formula used to calculate the estimated BESS power rating size is as follows:

$$P_{BESS} = P_{block} - P_{Wind} \tag{8}$$

where:

- P_{BESS} is the obtained BESS power rating at the worst-case scenario.
- P_{Wind} is the wind generation at the worst-case scenario.
- P_{block} is the block load size (20 MW minimum requirement).

If the resulting power rate is a negative value ($P_{BESS} \leq 0$) it means the OWF output exceed the block load demand required, and so there is no need of a BESS as BS support. Instead, if the resulting power is a positive value ($P_{Battery} \geq 0$) it means the BESS will have to discharge the mismatch power and support the WF to balance the required block load. It is important to remember that, although the resulting P_{BESS} is negative, the BESS is still required for the previous phases (e.g., the energization phase) of the BS process.

Resuming, the steps of the BESS sizing method are summarized as follow:

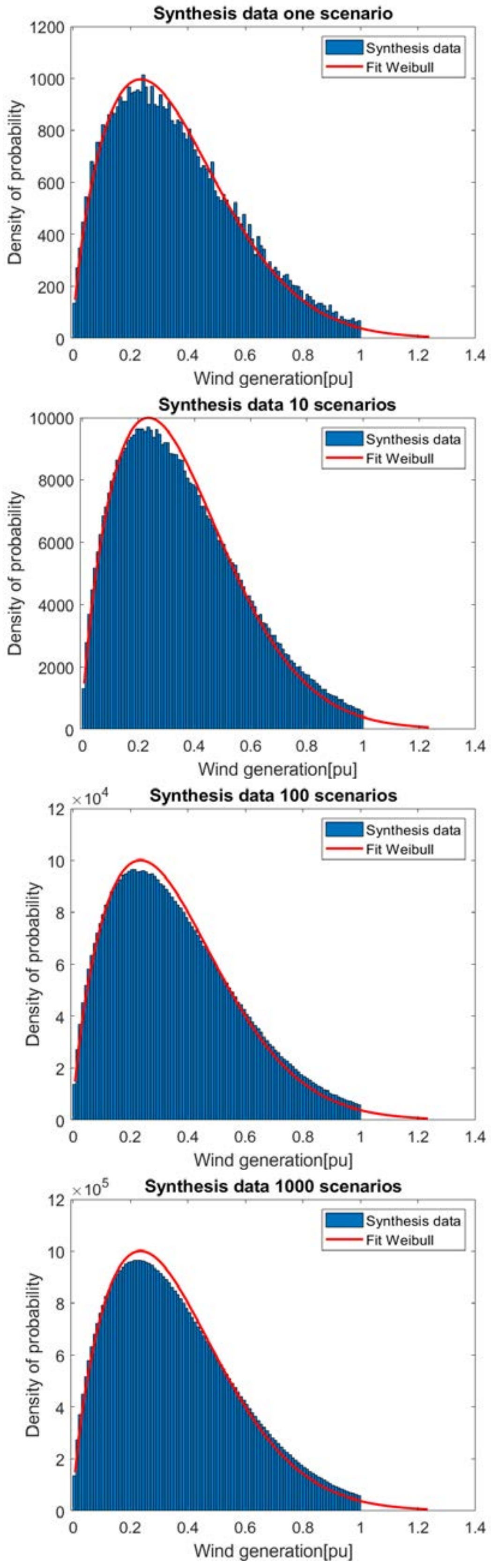

Fig. 5. Synthesis data generation fit to Weibull distribution for different scenarios.

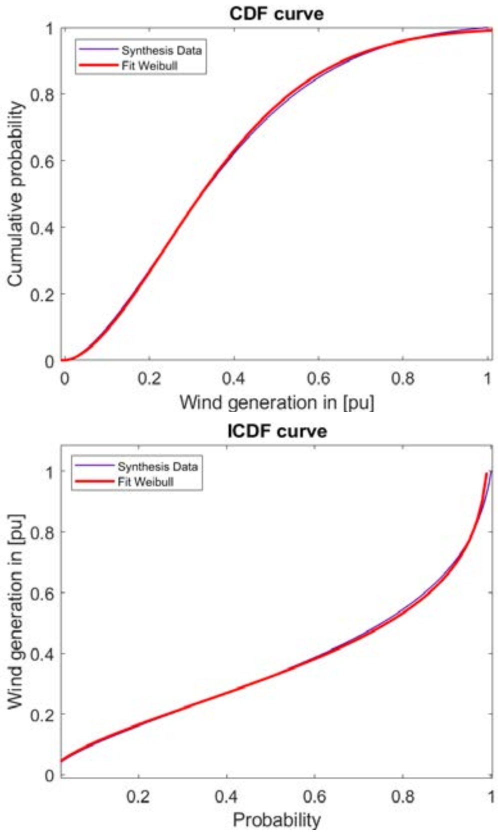

Fig. 6. Cumulative distribution function (CDF) and the inverse cumulative distribution function (ICDF) for synthesis data generation.

1) Evaluate the time series historical data.
2) Fit the historical data with a chosen distribution (Weibull for this project).
3) Generate synthesis data to better fit to the selected distribution.
4) Calculate the PDF, CDF, and ICDF for the estimated data.
5) Set the boundary value (the probability of getting the wind generation) in ICDF function to 0.1 (10 % probability) to estimate the worst case generation value.
6) Estimate the BESS power rating size at the worst-case using equation 8.

IV. RESULTS AND SIMULATION

A. Probabilistic Optimization Results

Tables II and III show the BESS size results for supplying 20 MW block load under minimum wind power generation at a 90% confidence level (worst-case) for the historical and synthesis data. Different OWF capacities have been used starting from 8 MW (single wind turbine case) to 400 MW.

It can be seen that the OWF using the Weibull distribution to estimate the historical data will not produce less than 0.102 pu at a 90% confidence level, While for the synthesis data, the value is 0.105 pu. However, the difference between the estimated worst-case wind power value for historical and

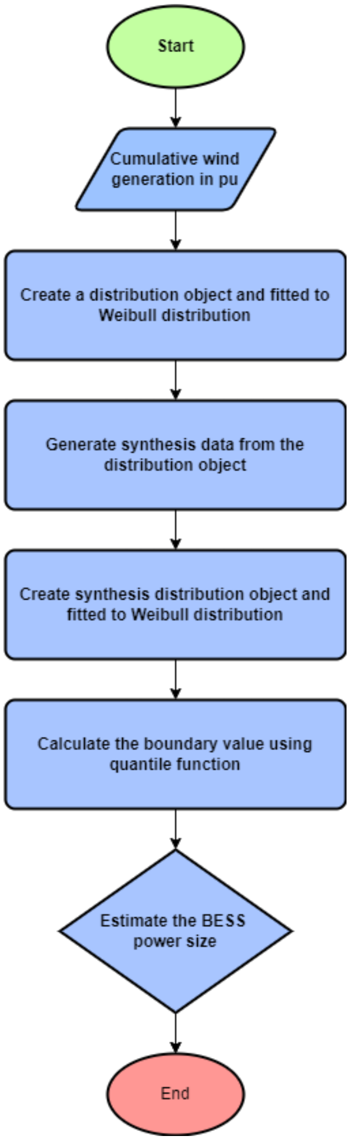

Fig. 7. Flowchart of the method applied to estimate the power rating size.

synthesis data is very small ($3e^{-4}$ pu), but this value will affect the size in the case of large wind farm capacity, as seen in the case of 400 MW.

The BESS power size has been calculated using equation 8. The negative value represents when the wind generation exceeds the block load demand, and the positive value means the discharging power to the block load. When providing power to block load, the black start problem is mainly related to the discharge power. Thus, the 400 MW can satisfy the minimum block loading requirement without the need for a BESS at the 90% confidence level.

It is worth mentioning here that the size of the BESS in terms of power and capacity is essential for the last step of black start because the time range required is in hours. However, it is not necessary for the energizing process because the problem is related to frequency regulation and the time needed ranges between 20 seconds to minutes [8], [3].

In addition, the minimum requirement provided by the British TSO (ESO) is delivering continuous power to block load for at least 10 hours. Therefore, the energy capacity results have been considered the minimum time required (10 hours) in calculating the energy capacity size.

TABLE II

Results for historical data estimation at 90% confidence level and 20 MW block load

Base capacity in MW	Wind generation pu	BESS power size in MW	BESS capacity in MWh
8	0.102	19.186	191.86
50	0.102	14.913	149.13
100	0.102	9.825	98.25
400	0.102	-20.700	0

TABLE III

Results for synthesis data estimation at 90% confidence level and 20 MW block load

Base capacity in MW	Wind generation pu	BESS power size in MW	BESS capacity in MWh
8	0.105	19.156	191.56
50	0.105	14.728	147.28
100	0.105	9.443	94.43
400	0.105	-22.221	0

In order to know when the BESS needs to be discharged to support the 400 MW OWF in the block load phase, the sensitivity analysis was applied for different block load sizes in case of synthesis data estimation and 90% confidence level. The results are presented in table IV. It can be seen that the BESS discharge when the block load size equal to 50 MW.

TABLE IV

Results for 400 MW OWF using synthesis data estimation at 90% confidence level and different block loads

Wind generation pu	Block load in MW	BESS power size in MW	BESS capacity in MWh
0.105	30	-12.194	0
0.105	40	-2.183	0
0.105	50	7.819	78.19
0.105	60	17.816	178.16

It can be observed that for large offshore wind farms such as 400 MW, the BESS is not needed for providing power to block load of 20 MW, but still, need power rate for energizing the wind farm and part of the grid.

B. Study Cases and Quasi-Dynamic Simulation Results

study cases were selected from the historical data for different seasons in 2019 to simulated in DIgSILENT PowerFactory using the quasi-dynamic tool to verify the results obtained from the method applied. The study cases are presented as follow :

1) One-Day Simulation: The one-day simulation model is selected randomly for different seasons to verify the black start requirement for the ability to deliver continuous power to a 20 MW block load for at least 10 hours. The confidence level for the scenarios are calculated using equations (**??**) and (5).

The simulation result for the 400 MW wind farm base value on a winter day is shown in Figure 8. It can be seen the lowest wind generation value is 0.349 pu, and the BESS power value is -119.503 MW. The confidence level of getting higher than 0.349 is 47% of the time. The negative sign in the BESS value means the OWF power output exceeds the block load demand, thus, the BESS is not needed for this case.

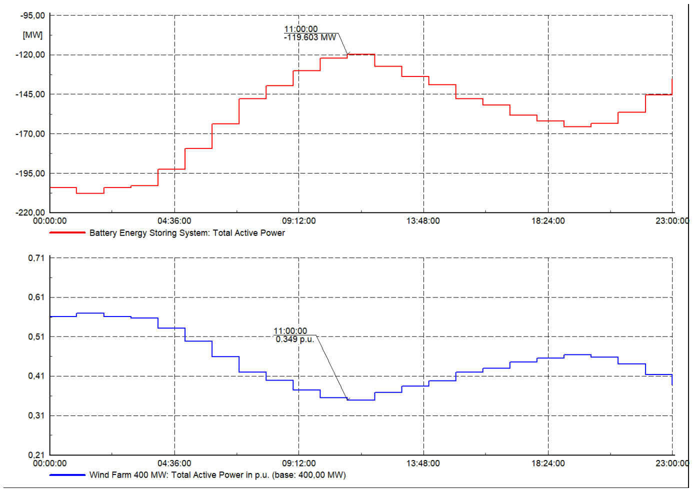

Fig. 8. Winter day on 01-01-2019.

2) Three-Day Simulation: The three days have been chosen in a row for the different seasons to simulate the black start problem and satisfy the resilience requirements of being ready to supply a 20 MW block load for 72 hours. The simulation result on a winter day is shown in figure 9. It shows that the lowest wind generation value during the three days is 0.241 pu,and the BESS power value is -76.481 MW. The confidence level equal to 65.79%. The negative sign in the BESS value means the OWF power output exceeds the block load demand, thus, the BESS is not needed for this case.

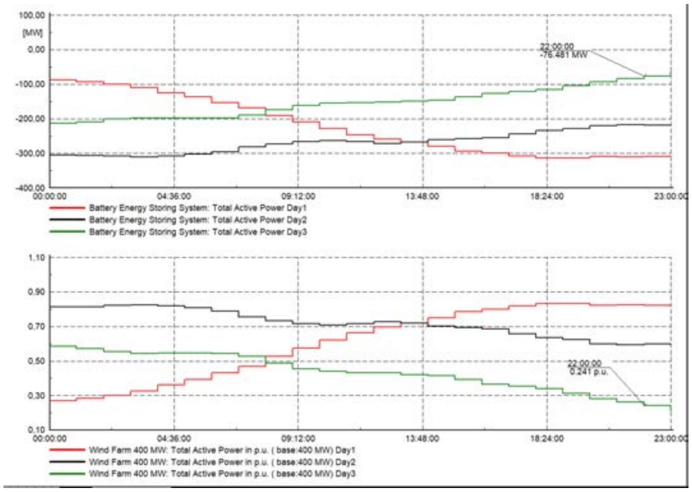

Fig. 9. Winter three days from 07-01-2019 to 10-01-2019

It can observe that the 400 MW OWF is already satisfying the minimum requirement for the block loading phase of the black start with confidence levels up to 90% without relying on the BESS.

C. Sensitivity Analysis

The main factors affecting the BESS size are OWF capacity, confidence level, and block load size. Moreover, the results show that the BESS is not needed for providing 20 MW in the case of 400 MW OWF, but it is needed when the block load size is 50 MW. Therefore, two new cases in quasi dynamic simulation have been investigated as a sensitivity analysis to confirm that the BESS will discharge when the block load is equal to 50 MW. The first case is a one-day simulation for different block loads ranging from 50 MW to 70 MW. The second case is a three-days simulation for a 50 MW block load. The study cases are shown as follows:

1) One-Day Simulation for Different Block Load: In this case, another season days has been picked up for sensitivity analysis to capture more generation values and confidence level scenarios, then a different block load of 50, 60, and 70 will apply to see what is the highest discharge battery at the highest confidence level.

Figure 10 shows the lowest wind generation is equal to 0.119 pu. The confidence level is around 87.34%. The resulting BESS power rating for all the block loads applied is positive, which means in this generation level, the BESS will discharge power of at least 2.519 MW for a block load size of 50 MW and a maximum of 22.519 MW for a block load size of 70 MW.

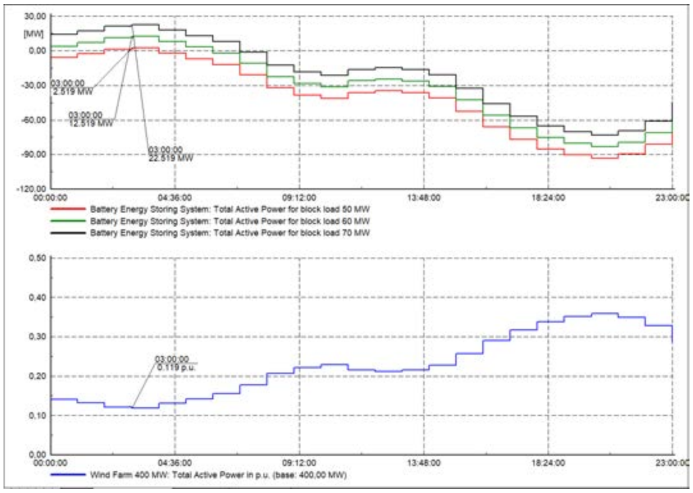

Fig. 10. Winter day on 31-12-2019.

2) Three Days Simulation for 50 MW Block Load: In this case, another three days of simulations were applied to study the resilience of supply for a block load size of 50 MW. The days have been chosen from 2018 to capture and simulate as much as possible real values with a different confidence level. Figure 11 shows the minimum wind generation is 0.286 pu with a confidence level up to 57.66%. In this scenario, the resulting BESS power rating is negative, which means the wind farm does not require any discharge from the BESS for the medium generation level.

In short, the 400 MW needs support from the BESS when the block load equal to 50 MW minimum at wind generation value corresponds to a confidence level higher than 87%, which confirms the results obtained from the optimization methodology.

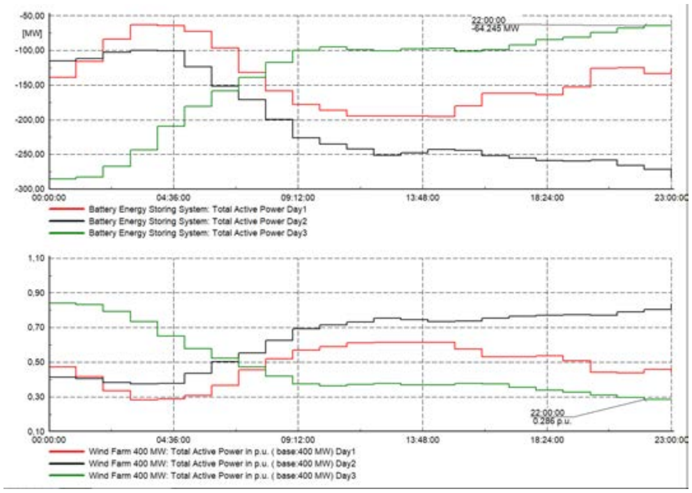

Fig. 11. Winter three days from 01-12-2018 to 04-12-2018.

V. CONCLUSION AND FUTURE WORK

A BESS sizing method for enabling OWFs to be a black start source is proposed in this paper. The probability method was applied to find the power rating of the BESS for the black start service under wind generation uncertainty. To do so, the Weibull probability distribution was applied to describe the cumulative wind generation data behavior, and estimate the worst-case generation value to find both power and energy size for the black start service. The analysis was carried out assuming the worst-case generation value corresponds to the power value with probability to happen at 10 %. In other words, the risk of getting less than the worst-case value is below 10 %, and therefore this power value is defined as 90 % confidence level in this project. Finally, the quasi dynamic simulation model of the black start process verified the results obtained from the optimization methodology. The results show that the optimal size of the BESS for supporting the OWF for the black start problem, particularly in the block loading phase, depends on two main factors, which are:

1) OWF capacity. In fact, large OWF can satisfy the minimum availability and block loading requirement without the need of BESS. However, the BESS is still needed for other requirements, such as energizing the wind turbines and part of the grid.
2) Worst-case generation value, which depends on the availability requirements provided by the TSOs.

In conclusion, the optimal size of the BESS for black start problem based on renewable sources relies on the services that the BESS should provide, and on the technical requirements that the TSO requires from the black start provider.

In this paper, the focus was to size the BESS power rating in MW needed to smooth the OWF output power for black start operation. However, for future work, simulating the net discharge energy in MWh needed when providing power to the block load phase will reduce the total cost of the BESS. An Optimal sizing of the BESS to enable the OWFs to participate in the black start market could be also a future work.

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