Comparison of Different Techniques for Offshore Wind Farm Reliability Assessment

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Abstract -- **The increase in wind power capacity installed worldwide has resulted in the necessity to include wind farms in power system reliability assessment. Especially, the installation of large offshore units connected directly to the transmission system has created the necessity of accounting for new aspects in the analysis. Various studies have been performed on the topic and many relevant factors of influence have been highlighted, but a complete assembly of all factors together has not been considered yet. This paper focuses on the comparison of different approaches for frequency and duration reliability assessments of offshore wind farms. The objective of the paper is to evaluate the most efficient technique, in order to represent a wind farm in the most realistic way and to perform a broad range of studies. Different aspects that influence the analysis are included in the paper, such as wind speed variability and randomness, system components, (wind turbines, internal grid cables and connectors to shore) failures and installation layouts. Two main approaches have been considered in this paper: One based on a sequential Monte Carlo simulation and one based on analytical methods with frequency and duration (F&D) analysis. The latter uses a probabilistic approach to define mathematical models of the system elements for calculating the output values, whereas the first model defines randomly the behaviour of each element for a number of sampled years and final results are evaluated as mean values. The computed results refer to the yearly output power and the capacity factor of the wind farm: These values, together with the required computation time and feasible future studies, are used in order to compare the efficiency and strengths of the two techniques. Furthermore, the possibility of distinguishing and evaluating effects of extreme wind conditions on the generation has also been used as a criterion in the comparison.**

Index Terms -- Offshore Wind Farm, Power System Reliability, Monte Carlo Simulation, Analytical Method, Wind Speed Time Series

I. Introduction

ELECTRICITY plays an important role in many human activities today and the interest in ensuring safe and secure electricity supply at reasonable costs has rapidly increased in the past 50 years. For this reason, reliability issues represent one of the main aspects to consider, when a power system has to be both planned and operated.

The term "reliability" has different definitions, depending on the purpose of the analysis: In a general sense, it indicates the overall ability of the system to perform its function adequately, for the period of time intended, under the operating conditions intended [1]. This definition can be applied to power system analysis: In this case, the evaluation may be performed using probabilistic solutions, which have evolved in the last 30 years [2]. These approaches can provide meaningful information that can be used in design, resource planning and allocation, as they consider probabilistic aspects of the system. Two main techniques have been developed so far, analytical methods and Monte Carlo simulations, and both solutions can be very powerful with the proper applications.

For general purposes, a complete power system can be categorised into three functional zones: Generation, transmission and distribution. Based on this classification, a power system is usually divided into three hierarchical levels (HL) for reliability studies [3]:

- HLI, which is mainly concerned with assessing the amount of generating capacity that must be installed in order to satisfy the system load;
- HLII, which refers both to generation and transmission systems and focuses on the composite problem of assessing the generation and transmission facilities in regard to their ability to supply the demanded energy adequately;
- HLIII, which adds the distribution segment to the HLII analysis and is usually studied to obtain suitable indices at actual consumer load points.

Beside these standard analyses, it must be considered that power systems have evolved towards a new structure during the last 15 years [3]. The installation of distributed generation units and renewable sources have created a number of new factors to take into account. In relation to reliability, these aspects have introduced elements, such as variability and randomness of "fuel" availability (e.g. wind or sun) and control of the generation managed by private operators, which involves new challenges, that power system owners have to consider in order to avoid problems during the normal operation of the system [3].

In relation to wind generation, onshore installations have widely increased in the past 20 years, but many countries have already moved their interest to offshore locations due to the congestion of onshore sites. Offshore installations can provide

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an increase in production due to better wind conditions of the location, however, new drawbacks must be taken into account. First of all, offshore sites can represent a problem for repair/maintenance actions during periods of harsh weather. Furthermore, they are expected to have larger size than onshore installations, and, due to the variability of the wind, this may cause problems in power system operations.

In the following list based on the available literature on the topic, a number of aspects that must be considered in connection with wind farm reliability assessment are highlighted:

1) Simulation of wind speed
2) Wake effects
3) Wind turbine technology
4) Offshore environment
5) Different wind speeds in the installation site
6) Power collection grid in the wind park
7) Correlation of output power for different wind farms
8) Grid connection configuration
9) Hub height variations

Many of the aspects are relevant for both onshore and offshore installations, but some of them (points 4, 5, 6, 7) have relevance mainly in connection with offshore conditions, as discussed in [4] and [5].

In this paper, two different probabilistic techniques are compared in order to evaluate the power system reliability with the inclusion of a large amount of offshore wind energy: One technique is based on an analytical method with frequency and duration (F&D) analysis, whereas the other technique is based on sequential Monte Carlo simulation. Both methods are based on time-dependent aspects (F&D or sequential), as the wind generation is characterised by daily and seasonal variations. The assessment is performed by computing a number of indices, later presented in this paper, in order to quantify the value of the generated energy. Moreover, aspects such as the required computation time, feasible future studies and the possibility of distinguishing and evaluating effects of extreme wind conditions on the generation are used in order to compare efficiency and strengths of the two techniques.

In section II of this paper, the two methods used for the comparison are briefly described, whereas in section III the analysed system and the computed results are presented together with the comparison of the techniques. In the last section, conclusions to the comparison are given.

II. Analysed Techniques

As previously mentioned, two methods are compared in this paper in order to provide frequency and duration assessment of offshore wind farm reliability: One method is based on sequential Monte Carlo simulation and one method is based on an analytical approach with F&D analysis.

Both techniques require different definitions and assumptions in order to perform the evaluations; however, it is possible to consider some common aspects that are relevant for the presented calculations.

- The calculation period is chosen equal to 1 year with hourly step (i.e. 8760 hours).
- Components of the wind farm included in the analysis are wind turbines, cables of the internal grid and connectors to shore.
- All system components are represented by a two-state model, i.e. each component is either in full service or out of service [2]. Furthermore, for the definition of the model, each component is characterised by its failure rate (λ) and its Mean Time To Repair (MTTR).
- In order to translate wind speeds into the power domain, the wind turbine is characterised by a power curve, that can be provided either by a manufacture or by a set of equations, as expressed in [6]. In the presented work, wind turbine features are based on a Vestas V90-3MW machine.
- The wind farm is represented by associating a wind speed model to the system component availability description.
- In order to define the number of wind turbines "effectively" available (i.e. number of wind turbines connected to the point of common coupling PCC and in service), a pseudo breadth first search (PBFS) method is used [7]. This approach produces the list of nodes in the wind farm that are connected to the PCC as output: If a node is in the list and an available wind turbine is connected to it, the generation of the node is added to the total wind farm output power. The use of this approach may increase the computational time of the process: For this reason, the PBFS method is utilised only if, in two following hours, there is a change in the current wind farm configuration (i.e. the number of effectively available wind turbines changes due to failure/repair of a cable or a connector to shore).
- Neither component overloading issues nor wind farm internal losses are included in the study. These aspects can be computed by load flow calculations: They may be relevant for large-scale installations and they must be taken into account, if the wind farm is used for HLII analysis. Since the purpose of this paper is only to evaluate the wind farm generation, load flow calculations are not included in order to avoid a huge computational time. However, some considerations on this topic can be found at the end of section III.B.
- For the calculation presented in this paper, wind speed measurements are obtained from 7-year data recorded at the Horns Rev wind farm location, Denmark. Data are recorded with 10-minutes average from the 14 May 1999 to the 13 May 2006: The amount of data, which should be equal to 368208, is 339492 due to some failures in the measurement equipment.
- Calculations are performed by a Pentium 1700 MHz and the software used is Matlab, version 7.1.

With these definitions and the application of the two techniques, a wind farm model is developed and it can be included in any kind of reliability assessment, such as HLI, HLII or HLIII.

In order to perform the comparison of the two methods, a number of indices that quantifies the wind generation are used:

1) IWP (Installed Wind Power) is the sum of the nominal

power of all the wind turbines in the wind farm;
2) IWE (Installed Wind Energy) is the product of the installed capacity and the number of hours in the period of interest;
3) EAWE (Expected Available Wind Energy) is the sum of the energies that the complete number of installed wind turbines produces in the period (no component failures are considered here) as a function of the wind speed;
4) EGWEWTF (Expected Generated Wind Energy With Wind Turbine Failure) is the sum of the energies that the complete number of installed wind turbines produces in the period including wind turbine failures;
5) EGWE (Expected Generated Wind Energy) is the sum of the energies that all effectively available (dependant on component failures) wind turbines produce in the period;
6) CF (Capacity Factor) is the ratio of EGWE to IWE.
7) GR (Generation Ratio) is the ratio of the power delivered to the PCC to the power injection generated by the wind farm (i.e. available power dependant on the current wind speed).

Moreover, the required computation time, feasible future studies and the possibility of distinguishing and evaluating effects of extreme wind conditions on the generation are used as criteria in the comparison.

In the two following sections, the two techniques used in this paper for the comparison are briefly described highlighting their most relevant aspects.

A. Analytical method

When an analytical approach is used for reliability assessment, the system under analysis is usually represented by mathematical models and direct analytical solutions are used to evaluate a-priori reliability indices from the models [2]. This means that the system is represented by states and a table is built with all the needed F&D information for each state.

In this paper, the wind speed is analysed considering the approach presented in [8]. Wind speed is a continuous physical phenomenon that evolves randomly in time and space: Since each value of time can be associated to a random number, a stochastic process can be used to model the wind speed. Thus wind speed can be considered as a stochastic process with a continuous state space, the wind speed value (that can be approximated as a discrete state space), and a continuous parameter space, the time [8].

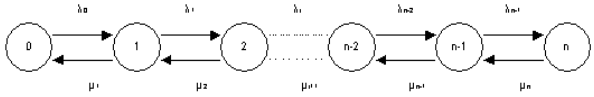

Fig. 1: Birth and death Markov chain (λ_i = transition rate from state i to state i+1; μ_i = transition rate from state i to state i-1).

In order to represent the wind speed in a way that considers both probability and F&D characteristics of the wind speed, a birth and death Markov chain (Fig. 1) with a finite number of states is used [8].

In order to define the model, the following assumptions are made [8]:

- Wind speed measurements are represented by a set of wind speed states.
- The wind speed model is statistically stationary, i.e. the stochastic behaviour of the wind speed is the same at all points of time irrespective of the point of time in focus.
- The distribution of residence times in a given state of the birth and death process is exponential.
- The probability of a transition from a given wind speed state to another state is directly proportional to the long-term average probability of the existence of the new state.
- Transitions between wind speed states occur independently on transitions between component states.
- From a given wind speed state, only the case of transitions to immediately adjacent states is considered.

The parameters of the wind model are calculated from a wind speed record: Measured values are sampled at regular intervals (e.g. an hour in the presented case) and the data that need to be extracted in order to calculate the model parameters, are the number of transitions from state i to $j = i \pm 1$ $N_{ws,ij}$ and the duration of the residence time in a state before going to a different state $D_{ws,ij}$ (if some transitions occur between nonadjacent wind speed states, the residence time duration is estimated by a linear proportion of the sampling time). State information are calculated as:

- State probability

$$p_{ws,i} = \frac{\sum_{j=1}^{M_{ws}} D_{ws,ij}}{\sum_{k=1}^{M_{ws}} \sum_{j=1}^{M_{ws}} D_{ws,kj}} \quad (1)$$

- State frequency [occ/y]

$$f_{ws,i} = N_{ws,i,i+1} + N_{ws,i,i-1} \quad (2)$$

- Average state duration [y]

$$d_{ws,i} = \frac{p_{ws,i}}{f_{ws,i}} \quad (3)$$

where M_{ws} is the total number of wind speed states. With the obtained data, a finite state Markov chain with exponentially distributed residence time is generated: The transition rates are calculated as:

$$\lambda_{ws,i\pm} = \frac{N_{ws,i,i\pm1}}{p_{ws,i}} \quad (4)$$

This procedure requires a small number of parameters to be calculated, but they should be generated from a wind speed record that is long enough to ensure a good approximation. The total number of states can finally be grouped in order to

reduce the total number of states and to decrease the computational time.

It must be noted that the wind speed ranges also can be divided into non-equally spaced states (i.e.: grouping states that generate the same output power): This can reduce the number of wind speed states and therefore reduce the total number of states in the system.

With the available wind speed measurements, the wind speed probability table used in this paper is shown in Table I (only few states are presented here), where "State" indicates the number of the system state, "Wind Speed" indicates the wind speed range associated to the state, "Prob" is the state probability, "Freq" is the state frequency, "Dur" is the average state duration, "Up" and "Down" indicates the state transition rates respectively for going to the adjacent up state and down state.

TABLE I
WIND SPEED PROBABILITY TABLE

State	Wind Speed [m/s]	Prob	Freq [occ/year]	Dur [year]	Up [occ/year]	Down [occ/year]
1	0-0,5	1,3E-03	8,7E+00	1,5E-04	6766,04	0,00
2	0,5 – 1,5	1,1E-02	8,3E+01	1,3E-04	6838,24	794,24
3	1,5 – 2,5	2,6E-02	2,2E+02	1,2E-04	5434,35	2829,39
4	2,5 – 3,5	4,1E-02	3,6E+02	1,1E-04	5313,82	3504,64
…	…	…	…	…	…	…
18	16,5 - 17,5	2,0E-02	1,8E+02	1,1E-04	3842,75	5152,29
19	17,5 - 18,5	1,2E-02	1,3E+02	9,9E-05	4056,80	6042,77
20	18,5 - 19,5	7,7E-03	8,3E+01	9,4E-05	4230,91	6469,20
…	…	…	…	…	…	…
42	40,5 - 41,5	2,0E-05	4,2E-01	4,8E-05	10468,79	10468,79
43	41,5 - 42,5	2,5E-03	2,1E+02	1,2E-05	0,00	83750,32

When the wind speed probability table is known, it is possible to associate the wind farm model to the system component availability data. For each of the wind farm states, a vector that includes a wind speed state and the status of each component in the system is defined in the following way [9]

$$\lfloor ws_i \; S_1 \ldots S_j \ldots S_N \rfloor$$

where ws_i is the ith wind speed state (i = 1…43 here), S_j is the status of component j (1 if available, 0 if out of service) and N is the total number of components in the system. Assuming e.g. a number of components equal to 53 (e.g. 25 wind turbines, 25 cables and 3 connectors), each wind farm state vector has length of 54 and the total number of states is $43x2^{53}$.

In order to define the set of system states, the following assumptions are made:

1) Failure and repair of each component are statistically independent.

2) Two connected system state vectors are different just in one element (i.e. it is assumed that the system moves from a state only due to status change of one of its components or change of the wind speed).

3) Due to the high number of states, it is assumed that a maximum number of three components may be out of service in the same wind farm state. As for the previous example, the total number of states is reduced to 1068894 from $3.87x10^{17}$.

When the complete number of state vectors is known, it is possible to calculate the probability of each state as:

$$p_i = \prod_j^{N_A} A_{comp,j} \cdot \prod_k^{N_U} U_{comp,k} \cdot p_{ws,z} \tag{5}$$

where A and U are the availability and unavailability of component j and k, respectively, N_A is the number of available components in state i, N_U is the number of unavailable components in state i and $p_{ws,z}$ is the probability of wind speed state z of state i. Due to assumption 3) it is necessary to normalise all probability values, in order to have the sum of all state probabilities equal to 1. State transition rates (measured in [occ/y]) are defined as a vector

$$\lambda_i = \lfloor \lambda_{ij} \rfloor \tag{6}$$

that includes all possible transitions λ of state i to state j and that has the length of the number of state N_i that are connected to state i. The other F&D parameters are calculated as:

- State frequency [occ/y]

$$f_i = p_i \cdot \sum_j^{Ni} (\lambda_{ij}) \tag{7}$$

- Average state duration [y]

$$d_i = \frac{p_i}{f_i} \tag{8}$$

All these values must be calculated for an F&D analysis, as they provide information on the duration of each event and its frequency of occurrence.

Due to the size of the problem, it may be convenient to reduce the total number of states with an aggregation procedure in order to obtain a representation that can be handled more easily in further calculations. This process is performed by aggregating states with similar output power in the same new state. In the presented case, it has been chosen to use an aggregation step of 5 MW (e.g. states with generation between 7,5 and 2,5 MW are aggregated into the same state) and the output power of the new state is calculated by weighting the output powers of the original states that are aggregated into the new state with their respective probabilities. Particular aggregation steps are used for the first two and the last two new states: Original states that generate the exact rated power and the exact zero power are aggregated respectively into the first and the last new states. Original states that produce between the rated power (excluded) and the rated power minus 2,5 MW are aggregated into the second state, whereas the second last new state is formed by the original states that generate between zero production (excluded) and 2,5 MW. This procedure is chosen in order to reduce the approximations of the aggregation process: The

total yearly energy generated by the wind farm is exactly the same with both complete and aggregated table.

As an example of this approach, considering a wind farm with 53 components and a wind speed table with 43 states, the assumptions previously mentioned and with the data presented in section IV of this paper, it is possible to obtain an aggregated table as in Table II.

The original 1068894 states are aggregated into 18 new states that are characterised by a set of parameters: "State" indicates the number of the system state, "Power" is the output power of the state, "Prob" is the state probability, "Freq" is the frequency of occurrence per year of the state, "Fr up/Fr down" indicate the cumulative transition rates of the current state for moving up or down, respectively, "Dur" is the average duration of the state and "Energy" is the expected energy produced by the wind farm in a period of one year.

TABLE II
AGGREGATED WIND FARM PROBABILITY TABLE FOR A WIND FARM WITH 53 COMPONENTS.

State	Power [MW]	Prob	Freq [occ/y]	Fr up [occ/y]	Fr down [occ/y]	Dur [y]	Energy [MWh]
1	75,00	4,35E-03	11,18	0,00	2572,50	3,89E-04	2855,94
2	73,77	1,10E-02	35,23	950,38	2242,50	3,13E-04	7129,45
3	69,96	6,41E-02	153,96	389,97	2012,00	4,16E-04	39281,91
4	64,93	6,38E-02	271,62	1509,40	2749,90	2,35E-04	36268,86
5	59,73	3,50E-02	300,22	3871,00	4697,00	1,17E-04	18332,77
6	55,02	4,01E-02	340,29	3874,20	4619,60	1,18E-04	19309,77
7	50,41	4,41E-02	361,85	3755,60	4446,40	1,22E-04	19481,27
8	45,24	5,11E-02	426,11	3868,60	4474,10	1,20E-04	20243,07
9	41,23	4,32E-02	363,51	3934,70	4482,00	1,19E-04	15598,98
10	34,95	8,46E-02	730,73	4119,00	4520,30	1,16E-04	25897,73
11	28,86	1,44E-02	126,71	4307,40	4510,50	1,13E-04	3632,70
12	26,41	7,60E-02	671,06	4357,30	4473,70	1,13E-04	17579,77
13	18,85	8,71E-02	780,99	4519,50	4449,90	1,11E-04	14375,29
14	12,98	4,03E-02	360,57	4566,70	4388,30	1,12E-04	4578,61
15	10,07	8,45E-02	741,79	4551,90	4226,00	1,14E-04	7452,94
16	5,19	1,18E-01	638,91	3029,00	2379,00	1,85E-04	5375,17
17	1,56	5,77E-02	499,28	4883,90	3765,90	1,16E-04	786,90
18	0,00	8,06E-02	221,41	2746,40	0,00	3,64E-04	0,00

It must be explained why the presented aggregated transition rates are called cumulative. During the aggregation procedure, it must be kept in mind that, since all state information are aggregated, it is not possible to distinguish all transition rates of each new state. For this reason, two cumulative transition rates are defined for each new state, one for up states (i.e. to states with bigger generation) and one for down states (i.e. to states with smaller generation): Each of these rates represents the transition rate of the new state for going to all states with a bigger (or smaller) generation. After having calculated the probability $p_{i\text{-}agg}$ of the new state as the sum of probability of all original aggregated states, these cumulative transition rates are computed as:

$$\lambda_{\pm,i-agg} = \frac{\sum_{i}^{N_{i-agg}} p_i \sum_{j}^{N_{\pm}} \lambda_{ij}}{p_{i-agg}} \tag{9}$$

where λ_{ij} is the set of transition rates of the original state i to other states, $N_{\pm}$ is the total number of states with greater (+) or lower (-) generated power, p_i is the probability of state i aggregated in state $i\text{-}agg$ and $N_{i\text{-}agg}$ is the number of original states aggregated in the new state. The other F&D parameters are calculated with (7) and (8).

B. Monte Carlo simulation

A Monte Carlo simulation estimates a-posteriori reliability indices by simulating the actual random behaviour of the system, either in a random or in a sequential way. As previously mentioned, a sequential Monte Carlo technique is used in this paper in order to evaluate the reliability of an offshore wind farm.

The used method is a standard Monte Carlo simulation that includes:

- Synthetic generation of yearly wind speed time series
- Wind turbine failures
- Internal grid failures
- Connector to shore failures
- Influence of offshore environment

The simulation is performed with the following steps ([2]):

1) Definition of wind farm layout and component data
2) Calculation of the wind speed probability table
3) During each sampled year,
   a) Calculation of a synthetic wind speed time series
   b) Random definition of the hourly availability of each component
   c) During each hour,
      α) Definition of the effectively available wind turbine
      β) Evaluation of the wind farm output power
      χ) Calculation of wind farm indices
   d) Evaluation of the result accuracies
4) Calculation of the final indices by average

The above-mentioned framework is the standard Monte Carlo simulation and further information can be found in the available literature (i.e. [2]): Therefore, only points 2 and 3.a will be explained in detail in the next section.

The availability of each component (point 3.b) is calculated considering the data as listed in Table III of section III.A and assuming an exponential distribution for both failure and repair residence times, as suggested in [2]. The three assumptions used for the analytical method (page 4), are not valid anymore in connection with the Monte Carlo simulation: More than three components can be out of service at the same time and it may be possible that more than one component fails independently during the same hour.

In 3.c.α, the term "effectively" means, as previously mentioned, that the wind turbine is connected to the PCC at the current hour and produces energy, if available. This calculation is performed with the described PBFS method.

As described in [10], it is necessary to fix some criteria in order to stop the simulation (3.d). In the proposed method, the following two solutions are considered: The inclusion of a maximum number of samples, in order to avoid never-ending simulation, and a stopping criterion. The stopping criterion is based on the evaluation of the coefficient of variation [10]

calculated for all the system indices: The index with the highest coefficient of variation is chosen as reference value, and it is compared to a predefined tolerance. The simulation continues as long as the tolerance is smaller than the selected coefficient of variation. In the presented study, the most critical index for the stopping criterion is EGWE.

Finally the generation indices are calculated according to the standard Monte Carlo approach by means of calculating the averages of all sampled results.

1) Wind speed time series

Since a new developed wind speed generator is defined, more details about points 2 and 3.a of the Monte Carlo simulation framework are given in this section. Two steps are required for the simulation of the wind speed.

The first step concerns the calculation of a wind speed probability table as discussed in section III.A (Table I). The main problem that occurs when using one table based on yearly measurements is that some seasonal characteristics of the wind speed measurements may be lost and consequentially relevant information for the analysis cannot be used. In this paper, the problem is solved by calculating tables based on monthly information instead of on yearly measurements. In this way, 12 monthly wind speed probability tables are calculated and used for generating 12 wind speed time series. These series are combined and a yearly time series that preserves seasonal information is obtained.

After having developed the tables, it is possible to proceed and calculate the random wind speed time series. The current wind speed can reside in one of the different mutually exclusive states presented in the wind speed probability table, and after being in the current state for a certain amount of time, it moves to one of the two adjacent states (if the current state is 1 or 43, the wind speed can move only to the up or down state, respectively). Since the phenomenon can be described by an exponential distribution [1,8] and the transition rates of each state are known, it is possible to calculate the time series with the following procedure:

1) Initialisation of the wind speed vector $ws(h) = ws^1$ and the time variable $t = 0$. In the case presented here, the initial wind speed value is chosen close to the average wind speed of the measurements (9 m/s).
2) For the generic step i^{th}, two random numbers U^i_1 and U^i_2, one for the up transition rate and one for the down transition rate, are uniformly generated in the interval (0,1).
3) The Time To Up (TTU) and Time To Down (TTD) of the current state is evaluated by means of equations

$$TTU^i = \frac{h}{\lambda_{up}} \ln\left(U_1^i\right) \tag{10}$$

$$TTD^i = \frac{h}{\lambda_{down}} \ln\left(U_2^i\right) \tag{11}$$

where h is the duration of the simulation period expressed in hours (i.e. for one year, h is 8760 hours, for one month of 31 days it is 744 hours), λ_{up} is the up transition rate and λ_{down} is the down transition rate of state ws^i. The smallest of the two values calculated from (10) and (11) defines which new state the current wind speed moves to and also how long it will stay in the current state before moving to a different state (e.g. if TTU < TTD, it is assumed that the current wind speed goes to the upper state after TTU hours).

4) Vector ws and variable t are updated, so that:

$$t^i = t^{i-1} + TTU^i \tag{12}$$

$$ws(t^{i-1} : t^i) = ws^{i-1} + 1 \tag{13}$$

where $(t^{i-1} : t^i)$ means "between time $t^{i-1}$and t^i" (here it is assumed that the wind speed moves up from the current state). It must be noted that, if t^i belongs to the same hour of t^{i-1}, vector ws is not updated, as the wind enters and leaves the current state during the same hour.

5) Steps 2-4 are repeated until t is equal to h.

In this way, a synthetic wind speed time series is obtained and it can be used for further calculations in the Monte Carlo simulation. The main advantage of this approach is that the random variation of the wind speed is taken into account and a realistic simulation can be thoroughly described. The main drawback is the long computational time needed to evaluate a new time series in every sampled year. The problem can be avoided by defining and storing a set of wind speed time series in advance (i.e. before running the simulation) and then calling the series during the computation: Since the wind speed series will not be calculated in every sample, the computational time will be reduced. For instance, approximately 10 s per sample may be saved by the storage of wind speed time series in the presented case. However, this procedure is not used in this paper.

In Fig. 2, three wind speed time series are compared: The measured wind speed time series in year 2004 (a), a synthetic wind speed time series based on a yearly probability table (Table I) (b) and a synthetic wind speed time series based on the 12 monthly probability tables (c). It should be noted that, whereas plots a) and c) have similar seasonal behaviours (high wind speed at the beginning of the year, low wind speed in the middle and again high wind speed during the last months of the year), plot b) has a complete random characteristic during the year, with high and low wind speed averages distributed during the year. This shows why the wind speed seasonal characteristic of the wind speed must be included in a sequential analysis and it justifies the use of monthly probability tables as simulation tool in order to preserve some information about the measurements. In the rest of the paper, all used synthetic wind speed time series are obtained from the 12 probability tables.

In Fig. 3, the average values of different wind speed time series are compared: Mean values of three years of the measurements (year 2000, year 2002 and year 2003), the total average of the measurements, the mean values of 1000 sampled synthetic wind speed time series, the total average of the 1000 samples. The figure shows that averages of the

samples lay between the measurement averages boundaries and that the "1000 sampled year – Total Avg" (9,27 m/s) differs from the "Total measurement Avg" (9,18 m/s) by less than 1%. This proofs that synthetic and original time series have the same behaviour regarding mean values.

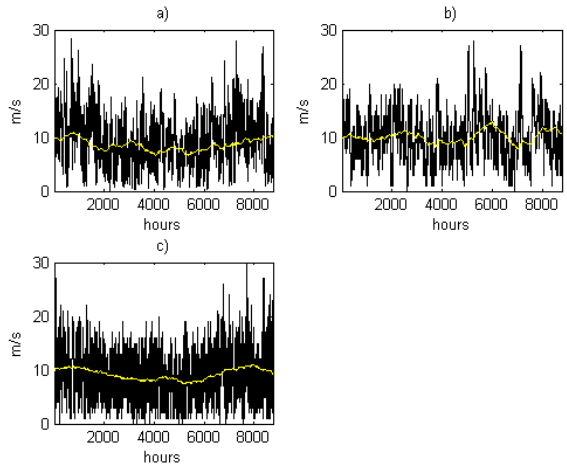

Fig. 2: Wind speed time series: a) original measurements (year 2004), b) synthetic wind speed time series based on yearly probability table, c) synthetic wind speed time series based on 12 monthly probability tables.

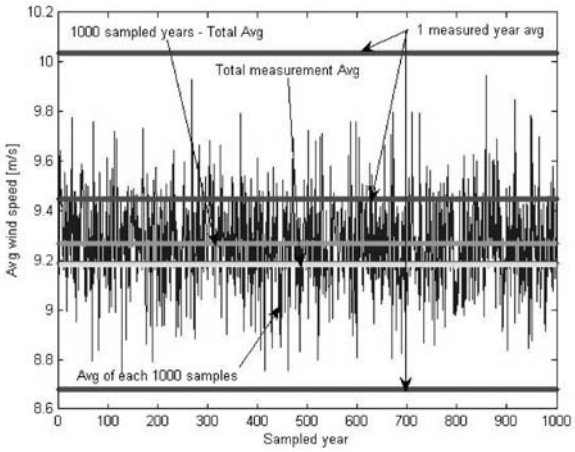

Fig. 3: Comparison of wind speed time series average values.

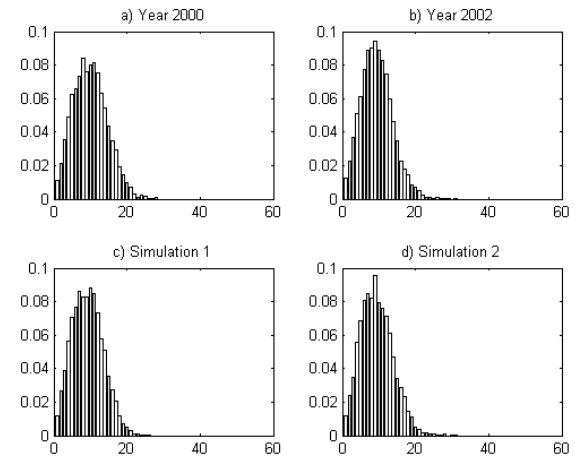

Fig. 4: Comparison of measured (plot a) and b)) and simulated (plot c) and d)) wind speed distribution function.

If the probability distribution function (pdf) of the time series (Fig. 4) is considered, it should be noted that both measured and synthetic wind speed time series approximate Weibull distributions. Plots a) and b) refer to measured years 2000 and 2002, whereas plots c) and d) regard two of the 1000 synthetic time series.

III. Comparison of Results

A. Analysed System

The system analysed in this paper is an offshore wind farm with 25 wind turbines, 25 internal grid cables, 3 connectors to shore and the layout shown in Fig. 5 [11] ("x" indicates a wind turbine, and a line represents a cable or a connector).

It is assumed that internal grid cables have the same electrical characteristics and same length (700 m) and connectors to shore (between nodes 26-29, 27-29 and 28-29) have the same electrical characteristics and a length of 10 km. Component data (λ, MTTR and availability) are presented in Table III. Data for wind turbines are obtained from [5], whereas data for cables and connectors come from [4]. The MTTR for cables and connectors is chosen as an average between summer and winter values [5]. It must be pointed out that due to the recent development of offshore wind farms, all data are based on assumptions and not on measurements.

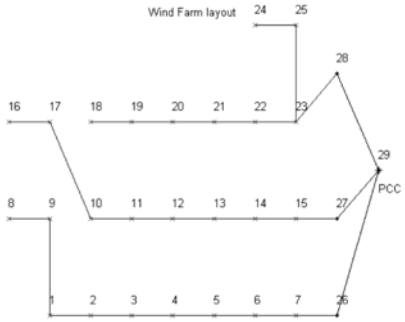

Fig. 5: Wind farm layout used for the simulation.

TABLE III
COMPONENT DATA FOR RELIABILITY CALCULATIONS.

	Nr	Failure rate	MTTR	Availability
Wind turbine	25	1,5 1/y	490 h/y	92,01 %
Cable	25	0,015 1/y/km	1440 h/y	99,83 %
Connector	3	0,015 1/y/km	1440 h/y	99,75 %

For the analytical computation, the wind farm is represented as shown in Table II: It consists of 18 states and all presented information are used for the calculation.

B. Results and Comments

The wind farm generation indices are shown in Table IV where also the required computational time is indicated. Only for the Monte Carlo simulation, the achieved accuracy of the results and the number of simulated samples are included. The last mentioned value, "Nr. of samples", represents the number of samples (= 50 years) that the simulation has to run in order to obtain the required accuracy of the results (0,5%).

First of all, it should be noted that the results presented here do not strictly require an F&D or sequential calculation

to be obtained and this would not justify the computational effort used for the representation of the two models. However, the aim of this paper is to show how to adopt the two probabilistic approaches for evaluating the wind farm generation and which requirements are needed for adding the wind farm model into HLI or HLII analyses. As soon as one of these studies is performed, it becomes relevant to have an F&D or sequential representation due to the stochastic nature of the wind: Therefore, the choice of procedure is explained.

TABLE IV
WIND FARM GENERATION RESULTS

Index	Unit	Analytical Method	Monte Carlo Simulation
1. IWP	MW	75	75
2. IWE	MWh	657000	657000
3. EAWE	MWh	277995,7	282188,1
4. EGWEWTF	MWh	-	260622,6
5. EGWE	MWh	258181,1	259204,8
6. CF	-	0,393	0,3945
7. GR	-	0,9345	0,9247
Simulation time	s	6371,78	1168
Result accuracy	%	-	0,5
Nr. of samples	-	-	50

Index 4 is not calculated according to the analytical method, because, using state vectors, it is not possible to distinguish causes of contingency due to single component failures, i.e. it is not possible to evaluate the wind farm generation solely by taking wind turbine failures into account.

Observing how the wind farm generation varies including different component failures (indices 3, 4 and 5), it can be explained why the inclusion of internal grid cable and connector failures may be relevant for the analysis. The difference between index 3 and index 4 (only wind turbine failure taken into account) is about 7,6% and it is justified by the availability of a wind turbine (Table III). The difference between indices 4 and 5 is about 0,6%, as it can be noted observing the availability of the other components (Table III).

Index CF indicates the capacity factor of the wind farm and it is around 39%. This value is high if compared to onshore installations, but it can be reasonable for offshore sites [12].

Index GR that represents the generation of the wind farm in relation to its component availability, has a value above 92% of the total generation: This can be explained considering the values assumed for the availability of each component, as shown in Table III.

When comparing the indices obtained with the two techniques, it must be noted that values are quite close and differences varies from 0,4% (CF) to 1,5% (EAWE). Differences can be justified by the assumptions made, which proofs that both solutions can be adopted for the evaluation. From a numerical point of view, similar results can be obtained.

When considering the computational time required by the two methods, it should be noted that the analytical approach needs more time to be completed mainly caused by the huge amount of system states (It is recommended that the computational time is reduced for a smaller system). On the other hand, the advantage of the analytical approach is that most of the time resources are used for generating the wind farm table (Table II) and after the values have been calculated once, the table can be stored and utilised directly for further calculations. This observation is not valid for the Monte Carlo approach, where the simulation must be performed each time the wind farm generation needs to be evaluated.

The compact representation of the problem provided by the analytical method has one main drawback in the representation of the zero production state (state 18 in Table III). In this state, three possible situations are included: Wind speed lower than the cut-in wind speed, wind speed higher than the cut-out wind speed and component failures that cause a full loss of generation. As these three conditions are aggregated together, it is not possible to distinguish the different reasons for zero production and this would represent a relevant reduction in the applications of the method, especially if extreme wind conditions are to be analysed. A solution for this problem can be found in avoiding the aggregation of the wind farm table, but this would result in a table with many states and this would exponentially increase the computational time and decrease the ease of handling the representation. This problem does not occur in the Monte Carlo simulation, as all system conditions can be distinguished during the calculation.

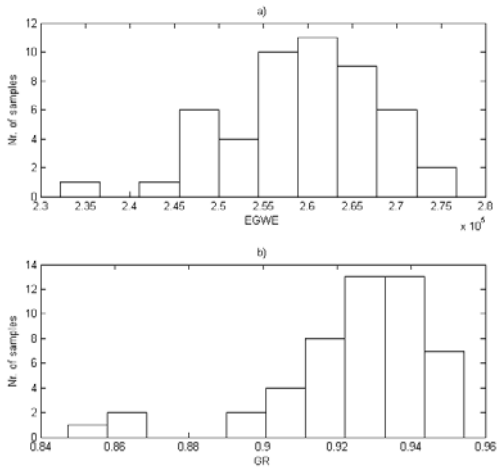

Fig. 6: Probability distribution function of index EGWE (a) and index GR (b).

Finally, considering the Monte Carlo simulation, it is possible to plot the pdf of each index. As an example of this, the distribution function of indices EGWE (plot a) and CF (plot b) are shown in Fig. 6. The use of these pdf's can be of help for predicting the behaviour of an index and its frequency of occurrence.

In order to consider the possibility of including the Monte Carlo simulation in more detailed power systems, the same calculations are performed using AC load flow. A standard Newton-Rhapson approach is used [13] and it must be computed during each hour of the simulation. As the computation of 8760 load flows per sample would increase the computational time considerably, a Power Transfer Distribution Factor (PTDF) is introduced for the analysis [13].

The PTDF helps to reduce the number of calculated load flows down to approximately 40% with a reduction of computational effort. However, it must be kept in mind that the PTDF represents a linearisation of the problem: Therefore, all results are approximated. Obtained indices are similar to the one presented in Table IV, e.g. EGWE is reduced to 255777,8 MWh due to the inclusion of power system losses in the calculations. However, the factor that really varies in this simulation is the computational time that increases up to 4712 s, and the same accuracy (0,5%) is reached after fewer samples (30 in this simulation, that means a time-consumption per sample of 157 s, whereas in the case without load flow, the time-consumption per sample is equal to 24 s). These two aspects (increase of time and decrease of number of samples) must be considered when including load flow calculations into reliability evaluations.

IV. Conclusions

In the last years, the increase of wind farm installations has resulted in the necessity to include these generation units into power system reliability assessment. Due to its stochastic nature, this technology has created a set of new aspects that must be faced in reliability evaluation. This paper focuses on different techniques for evaluating offshore wind farm generation for reliability purposes. Two approaches have been considered: One based on analytical methods with frequency and duration (F&D) analysis, and one based on sequential Monte Carlo simulation. By using these two methods, models for assessing the generation of the wind farm including variability of the wind speed and system component failures are calculated and compared. The comparison is performed on the base of a number of reliability indices, the computational time, the feasibility of future studies and the possibility of distinguishing the generation during extreme wind conditions. Both methods provide similar numerical results and on one hand, the analytical analysis, after having being calculated once, represents the fastest solution. On the other hand using a Monte Carlo simulation, wind farm operations under extreme wind conditions can be distinguished and index distribution functions can be obtained from the computation. Both techniques can be used for reliability evaluations of power systems with a large amount of installed wind capacity both for HLI and HLII analyses and the choice between them depends on the purposes of the study.

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