Windfarm Generation Assessment for Reliability Analysis of Power Systems

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ABSTRACT
Due to the fast development of wind generation in the past ten years, increasing interest has been paid to techniques for assessing different aspects of power systems with a large amount of installed wind generation. One of these aspects concerns power system reliability. Windfarm modelling plays a significant role in this assessment and different models have been created for it, but a representation which includes all of them has not been developed yet. This paper deals with this issue. First, a list of nine influencing Factors is presented and discussed. Secondly, these Factors are included in a reliability model and the generation of a windfarm is evaluated by means of sequential Monte Carlo simulation. Results are used to analyse how each mentioned Factor influences the assessment, and why and when they should be included in the model.

Keywords: Windfarm, Monte Carlo simulation, reliability assessment

Nomenclature

C_F	=	Windfarm capacity factor [-]
E		for clarification of symbols E, see Fig 2
E_R	=	Installed wind energy [GWh]
E_0	=	From installed capacity, expected available wind energy [GWh]
E_1	=	After internal turbine losses, expected generated wind energy [GWh]
E_2	=	After turbine faults, expected generated wind energy [GWh]
E_4	=	After connection cable losses, expected generated wind energy [GWh]
Factor	=	aspect which influences the availability of a windfarm
MTTR	=	Mean Time To Repair [h]
P_R	=	Installed wind power [MW]
PCC	=	Point of Common Coupling
R	=	Generation ratio [-]

1. INTRODUCTION
The exponential increase of wind production in the last ten years has posed new challenges for power system analysis, due to the difference of wind power generation from conventional power generation. In particular, windfarm components may fail in a different manner from

those in conventional power plants, and the primary energy resource of wind is variable and not constant.

One of these power system analyses refers to system reliability, which is highly influenced by wind generation. For this reason, it has been necessary to develop models for including wind generation into power system reliability assessment. Moreover, due to the recent development of large offshore installations, these models have needed some updates and improvements in order to take into account some aspects, which were not relevant on shore, but which represent issues offshore.

This paper considers this problem. Factors that are more relevant in offshore windfarm reliability are presented and a complete windfarm model is proposed. The paper is organised in the following sections:

- section 2: lists influencing Factors and discusses their relevance in offshore windfarm reliability assessment.
- section 3: presents a model for reliability assessment of a windfarm with the inclusion of the Factors, and describes the main steps of the sequential Monte Carlo approach used for the assessment.
- section 4: discusses the relevance of the Factors, applies the model to a generic windfarm and compares results of each simulation to evaluate the influence of each Factor on the model.
- section 5: applies the whole model to two different windfarms and makes conclusions.

2. FACTORS OF RELEVANCE

The influencing factors are [Barberis Negra et al (2007)]:

1. Wind speed randomness and variability
2. Wind turbine technology
3. Power collection grid
4. Grid connection configuration
5. Offshore environment
6. Different wind speeds within the installation site
7. Hub height variations
8. Wake effects and power losses
9. Correlation of output power for different windfarms

The list of Factors considers the availability of some of the main components (i.e. wind turbines and cables) in the windfarm and other elements that influence the modelling. In the following sections, some details are given for each of the mentioned Factors regarding their influence on windfarm modelling for reliability assessment.

2.1 Wind speed randomness and variability

Wind speed is the "fuel" of windfarms, and its availability represents the main resource for the generation. Wind speed availability is characterised by randomness and variability. Information on these two elements can be extracted from wind measurements and they must be carefully considered for the modelling of any windfarm.

When a windfarm model is considered and a sequential Monte Carlo approach is used for the assessment, as in this paper, wind speed's chronological nature must be preserved as well. This might be done by means of two approaches.

(i) Wind measurements can be directly applied as input to the model without any further manipulation. This approach reduces the effort for analysing wind information, but measurements have to be recorded for several years with a wide range of possible conditions in order to have a broad representation of the wind speed behaviour in the site.

(ii) If these data are not available, synthetic wind speed time series can represent an alternative and efficient solution. There are two main techniques which have been used for this purpose: one based on the combination of auto-regressive (AR) and moving-average (MA) models (discussed in Chen (2000)), and one based on Markov chain processes (presented in Milligan and Graham (1996)). Both approaches present advantages and drawbacks, but both can be very powerful with the proper application.

In this paper, both approaches (i) and (ii) are analyzed. The synthetic generator (ii) is based on a birth and death Markov process, but state transition rates are used for evaluating each state residence time instead of a transition matrix. Details and verification of this synthetic wind speed generator can be found in Barberis Negra et al (2007).

2.2 Wind turbine technology

Wind turbines are responsible for extracting electricity from the wind blowing through them. Many different concepts based on different technologies are available in the market, and the choice of one solution may influence the generation of the windfarm, since different components mean different capacity and different availability figures (e.g. failure rate and Mean Time To Repair T_R (MTTR). An overview of possible machines is presented in Van Bussel and Zaarijer (2001), Dowec Team (2003) and Gasch and Twele (2002), in which main options for offshore installations are discussed.

Regarding the modelling of wind turbines for reliability studies, a two-state model is usually defined: a machine is either fully available or out of service, without the possibility of generating in derated states, as described in Ubeda and Rodriguez Garcia (1999).

2.3 Power collection grid

Offshore windfarms usually occupy larger areas than onshore installations, mainly because more machines are employed and therefore a larger power collection grid length is needed. This introduces the issue of internal cable failures into reliability studies: since more cables are utilised, the probability of a failure increases and this must be included in the assessment. Failures of these components were usually neglected in older models, but interest in them has increased very much in the latest works. Some examples can be found in Zhao et al (2005) and Sannino et al (2006), where different figures and models are discussed to assess the influence of internal cables on windfarm reliability.

2.4 Grid connection configuration

The power generated offshore is transmitted to shore by means of the windfarm's grid connection. Depending on the size of the farm, different options have been employed, either with several cables rated at medium voltage (.e.g.. Burbo Offshore Windfarm has a capacity of 90 MW and three connectors to shore rated at 33 kV) or with one cable at high-voltage (e.g. 160 MW of Horns Rev are transmitted by one connector rated at 150 kV).

Connectors are usually highly reliable, but their failure may lead to extreme situations where all or a large part of the generated power cannot be transmitted to shore. This explains why they might be relevant in reliability studies.

These components are represented with two-state models, as this is a common practise in cable reliability representation. Some examples of analyses including these elements can be found in Zhao et al (2005) and Sannino et al (2006).

2.5 Offshore environment

The environment plays a relevant role in the availability of offshore windfarms. Extreme weather conditions can affect the operation of different components and influence the windfarm generation in different ways. For example, in Van Bussel and Zaarijer (2001), Dowec Team (2003) and Sannino et al (2006), it is suggested that

(i) MTTR may significantly increase during harsh weather (e.g. winter) due to the increase of the time to reach and repair a failed component;

(ii) failure rate may increase due to marine conditions or eventually due to the installation site's closeness to sailing routes (even if this is case is more unlikely);

(iii) component quality may improve in order to compensate problems in (i) and (ii).

In addition, the main problem with offshore windfarms is the definition of availability figures. Due to the relatively recent development of offshore installations, there are not many available data concerning failure and repair information of offshore windfarms. Consequently, large efforts have been made trying to "guess" offshore data from onshore figures, as discussed in Van Bussel and Zaarijer (2001) and Sannino et al (2006). These guesses have been used in this paper for the calculations.

2.6 Different wind speeds within the installation site

Offshore wind data are usually defined as a single time series which is often assumed to be valid for all wind turbines in the windfarm. In reality, the wind speed varies as a function of time and space, so the output of each running wind turbine is not equal to that of the others. For offshore farms where dimensions are larger than onshore windfarms, this Factor can represent an issue.

A well-known solution refers to aggregated models. An example of this can be found in Holttinne and Norgaard (2004), where a simplified multi-turbine power curve approach is utilised to simulate the smoothing effects on the aggregated power output from a number of wind turbines within an area. The model, which accounts for area dimensions and statistical data of available wind speed measurements, is applied to wind turbine power curve and wind speed time series.

2.7 Hub height variations

Wind speed measurements are usually recorded at a certain height, which does not necessarily coincide with the height of the hub. If the two heights are close to each other, original measurements can be directly used, but if this is not the case, some manipulations have to be done. There are different formulae to scale wind measurements to different heights. In this paper the following equation is used, as presented in Gasch and Twele (2002).

$$v_2(h_2) = v_1 \frac{\ln\left(\frac{h_2}{z_0}\right)}{\ln\left(\frac{h_1}{z_0}\right)} \qquad (1)$$

where index 1 refers to the measurement height, index 2 to the hub height, v is the wind speed [m/s], h the height [m] and z_0 is the roughness length [m]. The roughness length is a coefficient that depends on the structure of the surface where the wind is measured. Examples of roughness length values can be found in Ackermann (2005) and a value of 0.0001 m is utilised here (open sea).

2.8 Wake effects and power losses

Wind turbine spatial arrangement influences output power by means of wake effects. Furthermore, electrical and control system losses play a relevant role too in the assessment of output power, depending on size and design of the windfarm. These two elements reduce the total output of the windfarm and they might be included in a complete model. The simplest solution consists in using an efficiency coefficient which depends on wind direction, number of wind turbines, their spatial arrangement and power collection grid design. As an example, Ubeda and Rodriguez Garcia (1999) assume an efficiency coefficient, which includes both aspects, equal to 90-95%.

System losses can also be calculated by load flow analysis. In this way, they are evaluated in a more precise way, but load flow requires additional time for the calculation and it is therefore preferable to avoid it in sequential Monte Carlo simulations.

2.9 Correlation of output power for different windfarms

When a full power system is analysed for reliability studies, it is possible that offshore wind generation is located at different sites. At any one time, different locations have different wind speeds, which may well be correlated with each other with regard to distance and time, but not equal. This correlation is always less than 1, decreases with distance and time and depends on several aspects (e.g. local climatic and topographical characteristics), which make the modelling difficult to develop. However, there are many works which have dealt with this issue; some examples can be found in Ubeda and Rodriguez Garcia (1999) and Gibescu et al (2006).

3. MODEL FOR THE CALCULATION

The work presented in this paper describes a model for reliability analyses of windfarms including the main Factors that influence it. A general representation of the model consists of four as shown in Fig. 1. Inputs are the wind speed data (block a.), which are affected by Factors 1, 7 and 8 from section 2, and the availability of system components (block b.), which are influenced by Factors 2, 3, 4, 5 and 6 from section 2. Inputs are collected by the windfarm model (block c.), where the layout of the windfarm is defined as well as characteristics of the simulation. Outputs of this block are the final results (block d.), which can be in the form of both hourly power time series and system indices. Indices are useful since they can provide an instantaneous quantification of the yearly generation. A list of the most common ones follows:

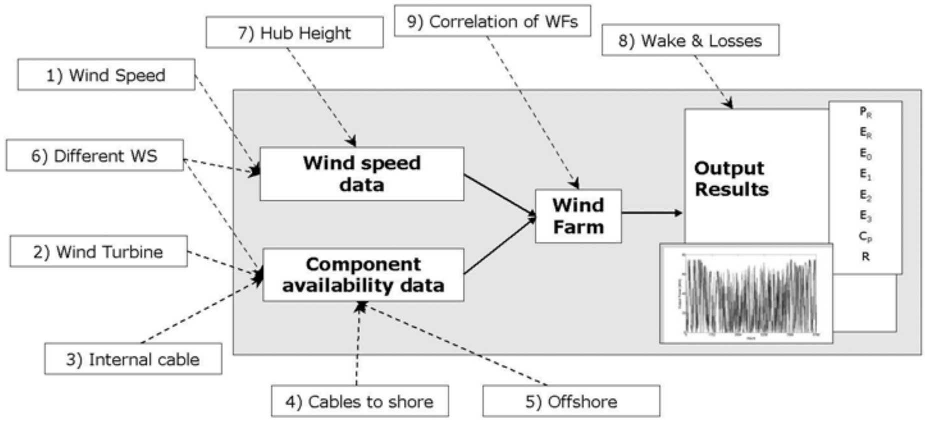

Figure 1. Windfarm reliability model: block diagrams and Factors of influence.

- P_R is the sum of the rated power of all the installed wind turbines;
- E_R is the product of the installed rated wind power and the number of hours in the period;
- E_0 is the generated energy in the period without accounting for wind turbine, cable and connector outages;
- E_1 is index E_0 including only wind turbine failures;
- E_2 is index E_0 including both wind turbine and internal cable failures;
- E_3 is the sum of the energy that all available wind turbines can produce in the period, including wind turbine, internal cable and connector failures;
- C_F is the ratio of E_3 to E_R and it represents the capacity factor of the windfarm;
- R is the ratio of the wind power delivered to the point of common coupling (PCC) to the power injection generated by the windfarm. This index states how much power is lost in the windfarm due to electrical component failure.

A representation of the relationship among some of the used indices is shown in Fig. 2. In section 0, the solutions used to include the Factors into the model are described, whereas some comments on the probabilistic technique used for the simulation are given in section 0.

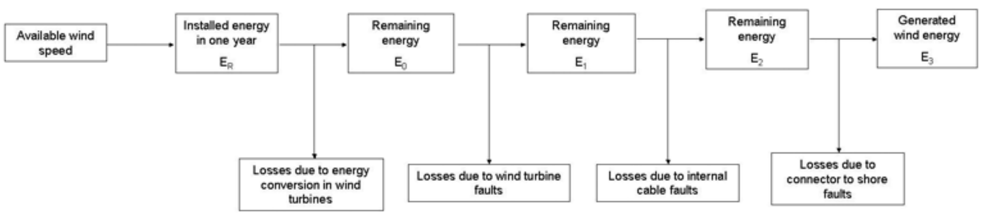

Figure 2. Relationship among reliability indices used in the analysis.

3.1 Factors included in the model

In this section, we describe different methods used to include the Factors within the windfarm model. A set of cases based on these inclusions is defined in section 0, where different analyses for the comparison are discussed.

Table 1. Components data for basic analysis				
	Length	Failure rate	MTTR	Availability
Wind turbine	-	1,55 1/y	490 h	92,01 %
Int. Cable	0,7 km	0,015 1/y/km	1440 h	99,83 %
Connector	10 km	0,015 1/y/km	1440 h	99,75 %

Table 2. Components data for cases 2 and 6			
	Failure rate	MTTR	Availability
Case 2	1,55 1/y	490 h	92,01 %
Case 6.1	1,10 1/y	490 h	94,19 %
Case 6.2	1,55 1/y	220 h	96,25 %
Case 6.3	1,10 1/y	220 h	97,31 %

Factor 1 (Wind speed randomness and variability) is considered by using a synthetic wind speed time series generator. The generator is based on two steps, as presented in Barberis Negra (-). In the first one, information about the measurements is extracted and a wind speed probability table is defined. In the second step, wind speed time series are randomly generated according to the information of the wind speed probability table. This model is used for all analysed cases, except for case 1 where the available measurements are directly applied.

Factor 2 (Wind turbine technology) is considered using different values for the availability of the wind turbines (i.e. failure rate and MTTR). The values used are listed in Table 1 and Table 2.

Factors 3 (Power collection grid) and 4 (Grid connection configuration) do not require a specific analysis, but they can be observed in the final indices. For example, index E_0 assesses the generation without any component failure, E_1 considers only wind turbine failures, whereas E_2 includes internal cables failure into index E_1, and E_3 shows the effect of failures of all components on the generation.s

Factor 5 (Offshore environment) refers to an offshore environment. In this paper, it is assumed that failure rates decrease due to improved components quality, and MTTR increases. Internal cables and connectors to shore may have larger seasonal variations in MTTR and therefore variable MTTRs are used in the simulation (Fig. 3). For wind turbines, a

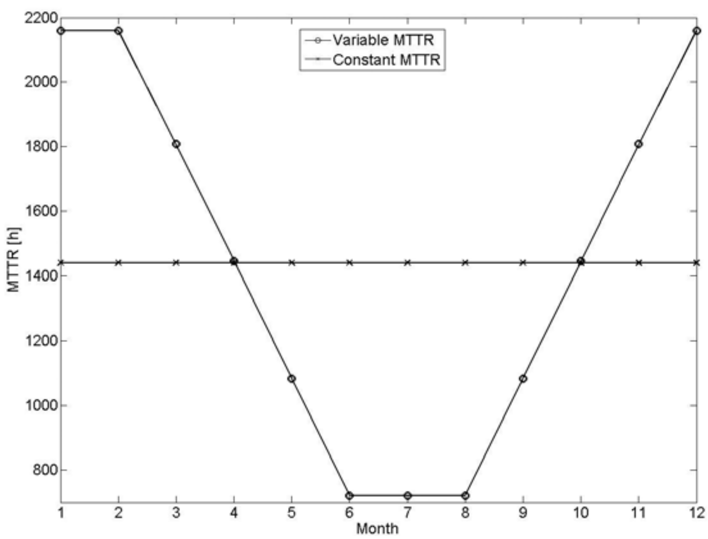

Figure 3. Monthly variable MTTR.

constant MTTR is utilised, because it is supposed that faulty machines can be more easily reached for repair actions even during harsh weather and therefore the variation of MTTR during the year is less influenced.

Factor 6 (Different wind speeds within the installation site) is considered using an aggregated model in order to take into account that wind speeds are not the same for each machine in the windfarm. This Factor has been described in detail in Holttinne and Norgaard (2004) and here the method has been applied. This approach considers that both wind turbine power curve and wind speed time series are influenced by the distribution of the wind turbines on the site: for this reason, both curves are aggregated and used as input for the Monte Carlo simulation. In Fig. 4 and Fig. 5, the influence of this aggregation on the power curve and on the wind speed time series is shown respectively. In both figures, it can be clearly seen that the larger the dimension of the area, the more influencing the aggregated model

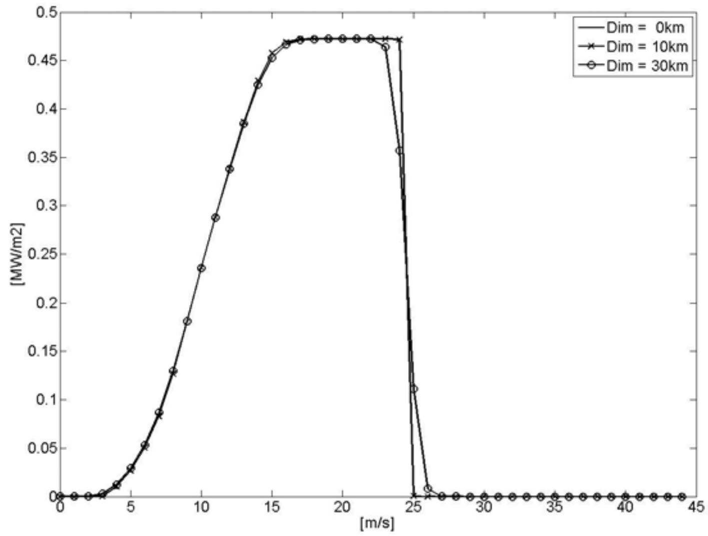

Figure 4. Normalised wind turbine power curve: original and aggregated for different area dimensions.

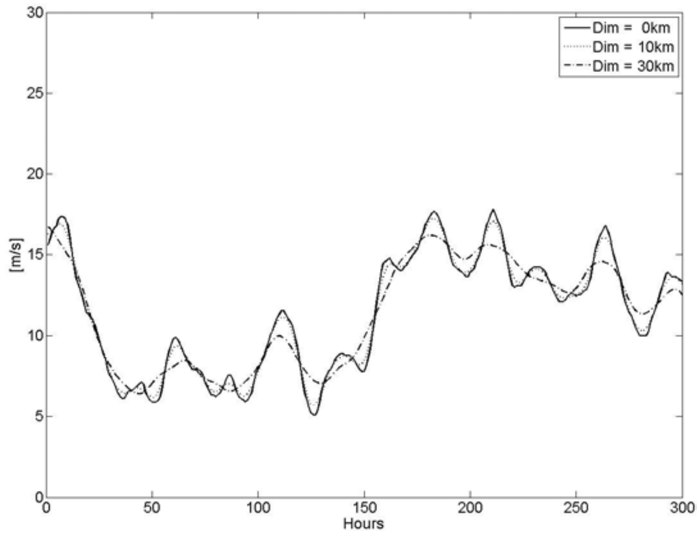

Figure 5. Original vs. aggregated wind speed time series for different area dimensions (first 300 hours of the year).

becomes. This dimension is obtained from empirical consideration in Holttinne and Norgaard (2004) and here it is chosen equal to the main diagonal of the windfarm. In the discussed results, two simulations are performed for case 4: one with a windfarm with dimension 10km (real assumption, case 4.1) and one with a windfarm dimension of 30km (case 4.2). This second representation is not realistic for the considered windfarm, but the choice is justified by the necessity of showing the influence of the aggregation on the results.

Factor 7 (Hub height variations) is included in the simulation using eqn [1]. The set of available measurements, recorded at 62m, are scaled to 100m, which is the supposed height of wind turbine hubs. Input data for the synthetic wind speed generator are extracted from these scaled time series. It has been decided to scale the measurements and not each synthetic time series in order to speed up the simulation, since eqn [1] is used only once during the definition of the input.

For Factor 8 (Wake effects and power losses), wake effects and power losses are included in the analysis by multiplying the obtained indices by an efficiency coefficient as suggested in Ubeda and Rodriguez Garcia (1999). A value of 93% is chosen.

Finally, Factor 9 (Correlation of output power for different windfarms) is not considered in this paper. Its relevance appears clear when a power system with several connected windfarms is analysed, but not in the study of a single windfarm.

3.2 Monte Carlo Simulation

As discussed in Barberis Negra et al (2006), there are two probabilistic techniques that can be used for reliability studies; one is based on analytical models and one on Monte Carlo simulation. Both methods have advantages and drawbacks and they can be very powerful with the proper application.

The work presented here is based on sequential Monte Carlo simulation. The reason for this choice is that with this approach it is possible to have more flexibility in the analysis, and a broader range of parameters can be analysed. The main drawback of a Monte Carlo simulation is usually its long computation time: since the studied system is not large, long computation time does not represent an issue here.

In this paper, a standard procedure for Monte Carlo simulation is followed, as in Barberis Negra et al (2006). Main steps of the analysis are given in the following list, considering a sample length of one year with hourly step.

1. Definition of windfarm layout and component data
2. *Application of eqn [1] for scaling wind speed measurements to hub height
3. Definition of the wind speed characteristics from the available measurements
4. *Application of the aggregated model
5. Then, for each sampled year,
    a. *Calculation of a synthetic wind speed time series
    b. Definition of the hourly availability of each component
    c. Then hourly,
        i. Definition of the effectively available wind power
        ii. Definition of the windfarm output power
        iii. Calculation of windfarm indices
    d. Evaluation of the result accuracies

6. Calculation of the final indices by averaging the sampled results
7. *Application of the efficiency coefficient.

Elements marked with stars (*) might be either applied or removed from the simulation.

Accuracy is evaluated for index E_3, which represents the most critical value in this analysis. Besides, a maximum number of samples is fixed in order to stop the simulation if the required accuracy is reached too slowly.

4. SIMULATION AND RESULTS COMPARISON

4.1 Models for the simulation

In this section, the performed analysis is presented. In order to compare the effect of each Factor on the model, seven cases are defined: each case includes one Factor and its results are compared to the reference case. Considered cases are the following.

- Case 1 is based on a standard model and the original wind speed measurements are used as input.
- Case 2 uses a synthetic wind speed time series generator (Factor 1). This case is assumed the reference case.
- Case 3 is the same as case 2 with a monthly variable MTTR (Factor 5) from Fig 2.
- Case 4 is the same as case 2 with the aggregated model of Holttinne and Norgaard (2004) applied to both the wind turbine power curve and the wind speed time series (Factor 6).
- Case 5 is the same as case 2 with different hub and mast heights (Factor 7).
- Case 6 uses different availability parameters for the wind turbine (Factors 3, 5).
- Case 7 corrects all final output indices with an efficiency coefficient (Factor 8).

Table 3. Results for the simulated cases

	Unit	Case 1	Case 2	Case 3	Case 4.1	Case 4.2	Case 5	Case 6.1	Case 6.2	Case 6.3	Case 7
PR	MW	75	75	75	75	75	75	75	75	75	75
ER	GWh	657.00	657.00	657.00	657.00	657.00	657.00	657.00	657.00	657.00	657.00
E0	GWh	285.85	281.17	281.10	300.74	302.83	297.50	281.74	281.40	281.39	261.49
E1	GWh	264.57	259.84	259.92	277.93	279.87	275.12	266.29	271.15	271.24	241.65
E3	GWh	263.22	258.50	258.70	276.49	278.42	273.76	265.10	269.81	269.88	240.40
E4	GWh	258.24	253.28	253.77	270.91	272.81	268.81	260.04	265.13	264.76	235.55
CF	-	0.393	0.386	0.386	0.412	0.415	0.409	0.396	0.404	0.403	0.359
R	-	0.910	0.908	0.910	0.900	0.900	0.910	0.929	0.946	0.945	-
Time per sample	s	~2540	~3260	~3270	~3220	~3130	~3300	~3270	~3270	~3240	-
Nr. of samples	-	1000	1000	1000	1000	1000	1000	1000	1000	1000	-
Accuracy	%	0.291	0.206	0.210	0.204	0.207	0.1994	0.206	0.189	0.196	-

The model is applied to two windfarm layouts:

- Burbo offshore windfarm, with 25 wind turbines (rated at 3 MW), a power collection grid with 22 cables and a grid connection with 3 connectors to shore (Fig. 6.a)
- Horns Rev offshore windfarm, with 50 wind turbines (rated at 2 MW), 50 internal cables and a grid connection with 1 connector to shore (Fig. 6.b)

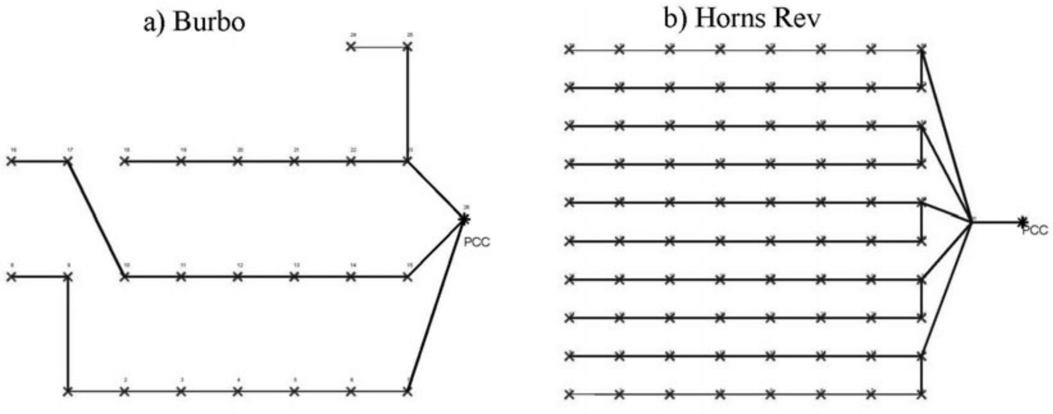

Figure 6. Windfarm layouts: Burbo (a) and Horns Rev (b).

The first layout is used to show how each Factor influences the model, whereas the second one is used only to assess the generation of a large windfarm with the complete model.

Components data are presented in Table 1: these data are utilised in all cases except for case 6) where values of Table 2 are used.

Wind speed measurements, used as input data either for the Monte Carlo simulation (case 1) or for the synthetic wind speed time series generator (cases 2-7)), are based on seven years of data from the Horns Rev location. When these data are directly applied to the Monte Carlo simulation, only four years are used (2000 to 2003) because they are the most complete years in the set of measurements. Other years are either partial (e.g. 1999 and 2006) or there is a lack of information due to equipment failure. When the synthetic wind speed time series generator is used, the available seven years of measurements are used as input data for the generator as explained in Barberis Negra et al (-).

Simulations are performed with a desired accuracy of 0.02% for index E_3 and a maximum number of samples equal to 1000. The chosen value for the accuracy is small compared to normal Monte Carlo analysis, but this choice is justified by the intention of having a large amount of samples for the comparison of different cases.

4.2 Comparison of results

Results of all cases are shown in Table 3. Reliability indices are included as well as the time required for the simulation, the number of samples for which each simulation has been run and the accuracy reached after the indicated number of samples.

First of all, the relevance of Factors 3 and 4 can be observed in the differences among indices E_0, E_1, E_2 and E_3, where different failing components are included (Fig 2, Table 3 and Fig. 7). Cables and connectors' availability influence the generation of the windfarm and a better representation is obtained if they are included in the model.

Considering case 1) and case 2), it can be noted that both simulations produce similar results, but values of E_3 are slightly different and this is due to the input data. In case 1), four years of measurements (2000 to 2003) are used, whereas the synthetic generator utilized the full range of measurements as input to the model (from May 1999 to May 2006). Years 2000-2003 have a larger average value than the seven years of measurements and this justifies the difference.

Fig. 8 shows that the behaviour of the simulations is different in the two cases. In case 1), the probability distribution of index E_3 is characterised by four peaks, as expected since four wind speed time series are repeatedly used as input in the simulation. In case 2) instead, the

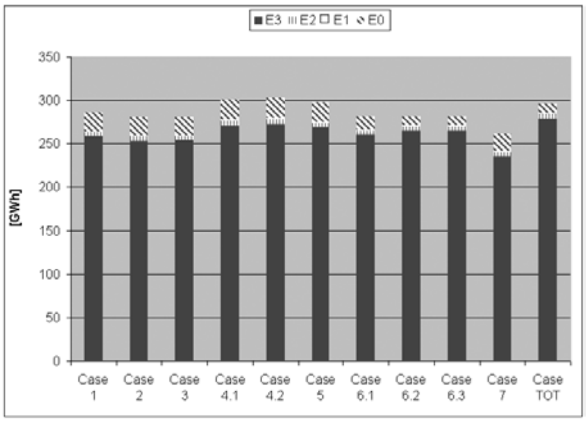

Figure 7. Graphic of the indices from Table 3.

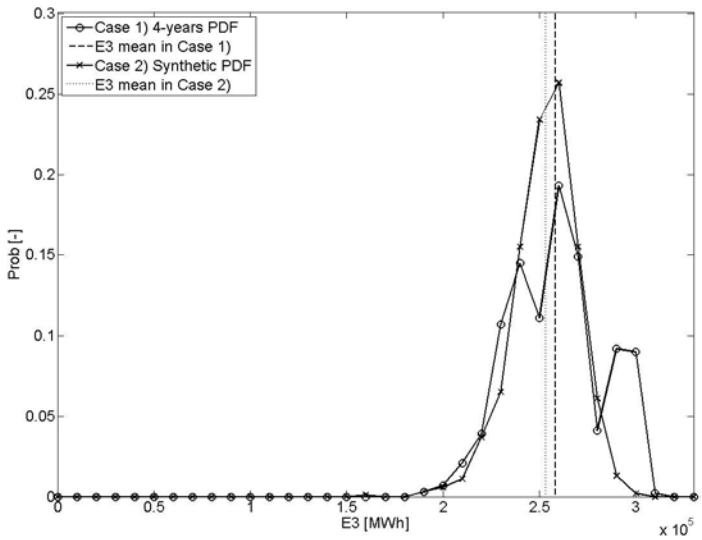

Figure 8. Probability distribution function of E_3 in case 1) and case 2).

distribution function is smoother due to the fact that the input wind speed time series changes at every sample. This justifies the use of a synthetic wind speed time series generator since it provides a wider and more complete range of wind speed time series to the analysis.

Considering convergence issues, Fig. 9 and Fig. 10 show the convergence and the accuracy variation of index E_3 respectively for cases 1) and 2). Case 2) requires a smaller number of samples in order to reach the same accuracies (Fig. 10). However, in Fig. 9 the index converges to the final value more slowly and the system is still far away from a steady-state condition when the required accuracy is reached. The smaller number of samples and the slower convergence can be explained considering again Fig. 8. As previously mentioned, the probability distribution function of case 1) shows four peaks that correspond to the four wind speed measurements used as input. Each output value oscillates around the steady-state condition that depends on its wind speed input (one of the four peaks). Therefore, the final result is a sort of average among the four steady-state points and a certain amount of samples is necessary before the inclusion of each additional sample does not sensibly influence final results. This also explains why, when the desired accuracy is reached, the simulation maintains a stable behaviour. In case 2), the use of a synthetic wind speed as input provides only one value (i.e. the steady-state value), which each output oscillates around. Moreover, since the accuracy is evaluated according to the current estimated value (e.g. the estimated value that depends only on the number of already performed samples), the number of samples for reaching the required accuracy is not sufficient in order to avoid that different output influence the final result of the simulation.

Finally, considering the computation time of the two simulations, it can be noted that case 1) is approximately 10 minutes faster than case 2) (i.e. 0,7 seconds slower per sample). This is reasonable, because in case 2) a synthetic wind speed time series is generated for each sample and some additional time is needed. If a set of pre-stored synthetic time series is recalled in case 2), the computation time decreases to approximately 2590 seconds and this value is similar to the one in case 1).

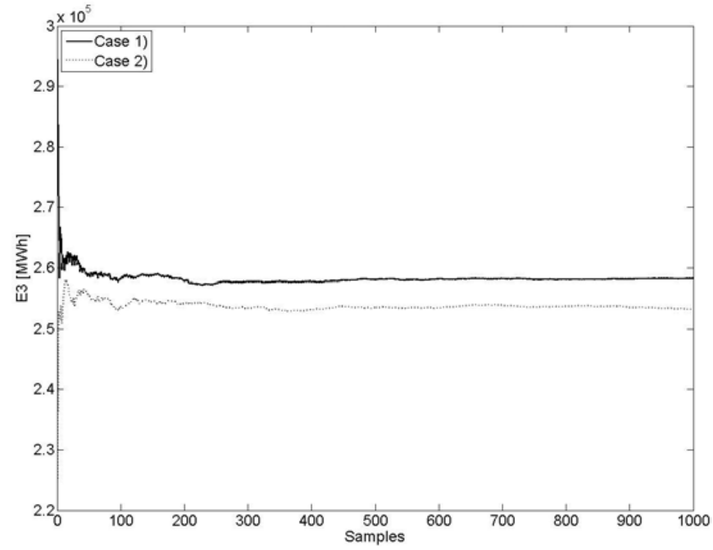

Figure 9. Convergence of E3 in case 1) and case 2).

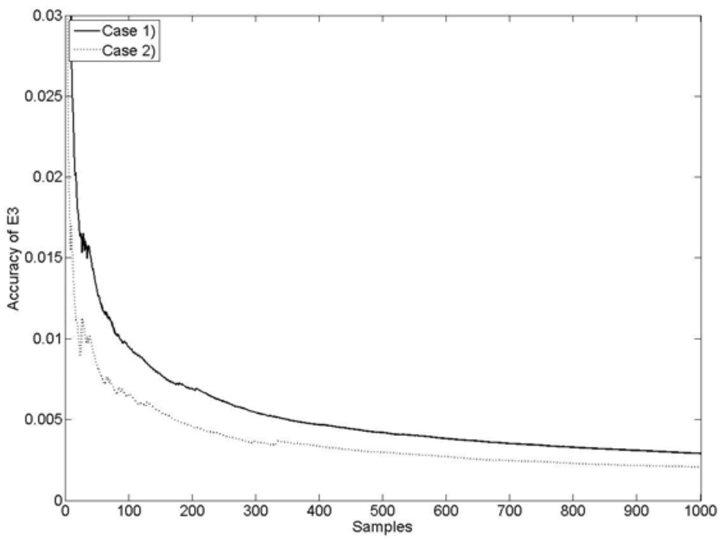

Figure 10. Accuracy variation of E3 in case 1) and case 2).

Comparing case 3) to case 2), it can be noted that, even if the average MTTR is the same (i.e. approx 1440 hours) and E_0 is slightly higher for case 2), the total generation of case 3) (index E_3) is higher (i.e. approx 0.2%). This can be explained by the fact that, in each sample, it is supposed that the windfarm is fully available at the very first hour of the sampled year. This means that, even if faults occur randomly, they are more unlikely to occur at the beginning of the year (i.e. when the MTTR is higher) and therefore a shorter time to repair can be expected which cause higher generation. However, since the difference is very small, the model can be considered valid also for the analysis performed here. A future development may consider evaluating the generation of the windfarm for its entire lifetime (eg 20 years) instead of for a single year in order to solve the problem of the initial state of the system.

In case 4), the main consideration regards the fact that the chosen dimension of the area must be larger than 10km in order to influence the results. It must also be considered that the used model from Holttinne and Norgaard (2004) has been developed for broader areas and that it is based on empirical considerations. However, the use of the aggregated model shows that the windfarm output is larger than the case in which it is not considered. This can be explained considering that the wind speed time series is aggregated in order to smooth all high and low peaks in the time series. Therefore low wind speeds are not considered as well as very high ones (as it can be seen in Fig. 5) and this increases the generation of the windfarm.

If case 5) is compared to the reference case, it can be noted that the generation is approximately 6% higher than in the reference case. The height of the wind speed has been increased and this causes better wind conditions (e.g. E_0). One important issue about the use of eqn [1] must be mentioned: since the windfarm generation is evaluated using integer wind speed values (i.e. wind speed states), the use of eqn [1] becomes interesting if the wind speed moves to the next wind speed state and a higher output power can be calculated. In the presented case, where a difference of 38m between hub and mast heights is used, the use of the formula shows its effects at wind speeds equal to or higher than 14m/s. For lower values, the wind speed is not influenced by the new height and the same output power as the original one is obtained.

This means that Factor 7 must be taken into account only if the difference between hub and mast heights is significant. This Factor can be observed in Fig. 11: eqn [1] is applied to the original measurements, considering two different hub heights (i.e. 100 m and 150 m). Case with hub height of 150 m is used only in Fig. 11 in order to highlight the influence of hub heights. In the figure, it is possible to note that for high values of wind speeds, the influence of eqn [1] is relevant, whereas for low wind speeds, the difference between original and scaled time series can be neglected. Moreover, the greater the difference between mast and hub heights is, the more relevant the difference between original and scaled wind speeds is.

For these reasons, it can be concluded that the use of eqn [1] is relevant for assessing windfarm generation, but it produces some influences if mast and hub heights are sufficiently different.

In case 6) it can be noted that the use of a better reliability figure for the wind turbines increase the total generation. It is therefore an important issue to reduce both parameters. However, due to the recent development of offshore installations, it is not simple to collect enough information on reliability figures of windfarm components. Used values are only "guessed" according to onshore data and therefore they cannot be considered completely realistic.

Finally, considering case 7), it can be noted how both wake effects and system electrical losses decrease the generation of the windfarm. The use of a constant coefficient is an

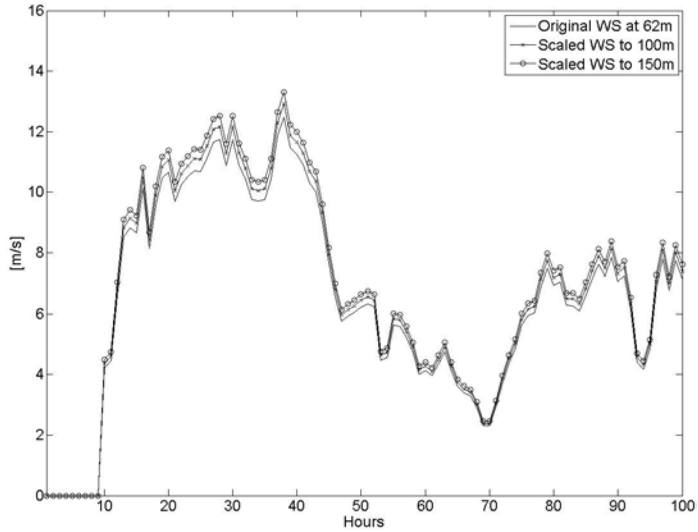

Figure 11. Influence of eqn [1] on wind speed time series (first 100 hours of the year).

Table 4. Results with all the factors included in the model with and wothout wake effects

		Burbo	Horns Rev		
		No efficiency	With efficiency	No efficiency	With efficiency
PR	MW	75	75	160	160
ER	GWh	657,00	657,00	140,16	140,16
E0	GWh	318,71	296,40	681,56	633,85
E1	GWh	307,13	285,63	656,88	610,90
E3	GWh	305,81	284,40	652,70	607,01
E4	GWh	299,79	278,81	639,78	594,99
CF	-	0,456	0,424	0,456	0,424
R	-	0,940	-	0,938	-
Time per sample	s	~3260	-	~6280	-
Nr. of samples	-	1000	-	1000	-
Accuracy	%	0,202	-	0,272	-

approximation that is reasonable in this contest: a more detailed approach should evaluate losses and wake effects for each wind speed state, since these elements are dependent on the current input wind speed. Furthermore, it is not possible to evaluate index R in this case: efficiency coefficient includes both electrical losses and wake effects and R is influenced by the losses, which are a characteristic of the windfarm grid, but not by the wake effects, which reduce the available wind speed. A solution for this might be to divide the efficiency coefficient into two elements; one for the electrical losses and one for the wake effects. This issue will be included in further improvements of the model.

4.3 Analysis with complete model

According to previous sections, a calculation with the full model is presented in Table 4 for both windfarm layouts.

The model includes the following characteristics:

(i) A synthetic wind speed generator is used to create the wind speed input to the model.

(ii) Wind turbine availability data are from Table 2, case 6.3, whereas cable and connector data are from Table 1.

(iii) The aggregated model is applied to both wind turbine power curve and wind speed time series.

(iv) Eqn [1] is used to scale the original wind speed measurement recorded at 62m to the assumed hub height, which is equal to 100m.

(v) An efficiency coefficient is chosen equal to 0.93 and it includes both power losses and wake effects.

Comments on the results provided in previous sections are still valid for the values in Table 4.

5. CONCLUSION

Due to the fast development of offshore wind generation, it is important to understand and assess the behaviour of power systems with large capacities of installed wind generation. One relevant characteristic regards the reliability of the power system; different models have been developed for this assessment and windfarm modelling plays a relevant role in them. This paper deals with this issue. First a list of nine Factors, which influence the modelling are presented and discussed. Secondly, these Factors are included in a reliability model, and the generation of a windfarm is evaluated by means of sequential Monte Carlo simulation. Results are used to analyse how each Factor influences the evaluation and why and when it should be included in the model. Main conclusions from the analysis are summarised in the following.

- A wide range of wind speed time series provides a more comprehensive power output of the windfarm, and therefore a larger overview of possible windfarm behaviours can be observed (Fig. 8). This justifies the use of a synthetic wind speed time series generator.
- Large differences between mast and hub heights must be considered in order not to underestimate the output power. However, if the difference is small, this effect is negligible.
- If a windfarm occupies a large area, hourly wind speed values may be different for wind turbines located far from each other. A solution to this might be to introduce a model for aggregation, which operates on both the wind turbine power curve and the wind speed time series, as suggested in Holttinne and Norgaard (2004).
- Due to offshore locations, component availabilities are more influenced by the environment than in onshore installations (Tables I and II). Moreover, since the MTTR can be somewhat different depending on the season, a monthly MTTR is used here for internal cables and connectors, with larger values in winter months, smaller values in summer months and values with linear variations in other seasons.
- Wake effects and power losses can play a relevant role in reducing the generation of a windfarm. The latter reduces the output of the windfarm due to electrical losses in the windfarm grid. The former depends on the location of wind turbines in the windfarm and is responsible for reducing the available wind speed. These two effects can be aggregated into an efficiency coefficient, which is applied to index E_3.

- Availability of internal cables and connectors to shore was not considered in reliability assessment of onshore windfarms, but their importance has increased for offshore locations, as it can be noted by looking at the differences among indices in Tables III-IV and Fig. 7.
- The correlation among windfarms in a power system is a relevant issue, since wind speeds that flow through them are correlated in a way, which is dependent on distance and time between their locations. In current literature, there are some available models for this issue and, when the discussed model is used for assessing power system reliability, some of these representations have to be used.

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