Evaluation of Synthetic Wind Speed Time Series for Reliability Analysis of Offshore Wind Farms

C.J. Smith[a], C.J. Crabtree[a], P.C. Matthews[a]

[a]Energy Group, School of Engineering and Computing Sciences, Durham University

I. Introduction

To meet EU renewable energy targets for 2020 and beyond, the Levelised Cost of Energy (LCoE) of offshore wind needs to be reduced from the current £140/MWh to below £100/MWh [1]. As Operation and Maintenance (O&M) accounts for around 30% of LCoE [2], researchers have carried out reliability studies on offshore wind to explore the root causes of these costs.

A unique characteristic of wind generation that impacts O&M is the stochastic nature of the fuel. This adds complexity to turbine operation and impacts the available maintenance opportunities, known as weather windows [3]. A weather window is defined as a point in time where a maintenance team could be dispatched to repair a component as the wind speed is below a threshold for a sufficiently long time period to carry out the repair. Weather windows are particularly critical for offshore O&M.

The wind resource also adds uncertainty to the expected loss of generation revenue during turbine downtime. Therefore reliability studies need to accurately capture the elements of the wind resource that impact turbine and farm O&M.

To carry out this reliability analysis a site specific wind speed dataset for the lifetime of the farm is essential. Typically this data is collected for a year prior to turbine construction, with future data skewed due to farm wake effects. Therefore a method for synthesising wind speed time series (WSTS) from limited data is required. The use of synthetic WSTS also allows for reliability examination under a range of wind speed scenarios.

Due to the complexity of wind speed data this is not a trivial task and all characteristics of the wind speed may not be captured using one modelling technique. To ensure a suitable model is chosen a list of reliability analysis specific criteria is needed.

This paper formalises the desirable attributes of synthetic WSTS for use in reliability analysis of offshore wind farms by formulating a list of key criteria. WSTS simulators were used to produce synthetic WSTS which were compared with these criteria to determine the most suitable simulator.

II. Approach

This section outlines the original WSTS data used for benchmarking, the measurement criteria used to assess synthetic WSTS quality, and the WSTS models assessed.

a. Benchmark Data

To assess the quality of WSTS simulators, an original data set is needed. The data was taken from the meteorological mast at the Egmond aan Zee wind farm [4]. Wind speeds from a height of 70 m at 10 minute intervals from 01/07/2005 to 30/06/2006 were used.

b. Desirable Criteria for Synthetic WSTS

To determine the suitability of synthetic WSTS for reliability analysis a list of criteria has been created for comparison with the original WSTS. These criteria have been chosen as the results of any reliability analysis using synthetic WSTS will be sensitive to the accuracy of these parameters. The synthetic WSTS should replicate the original data's:

1. Total energy availability in the wind resource.
2. Energy availability from a typical turbine.
3. Cumulative time at all wind speeds.
4. Number of transitions between wind speed states.
5. Longer term seasonal trends and occurrence of sustained low and high wind conditions.
6. The underlying statistical relationships, determined by the sample auto-correlation function (ACF), in the original WSTS.

To make these criteria measurable the calculation for the original and synthetic WSTS needed to be defined.

Note the wind speed data was discretised into 1 m/s states.

1. To quantify energy availability in the wind, the expected power densities ($E(p)$) of original and synthetic WSTS were computed (1). $E(p)$ was used to remove any un-required information such as turbine size and turbine life span.

$$E(p) = \sum_{u=0}^{u_{max}} 0.5\rho u^3 F(u) \qquad (1)$$

   Where ρ is air density (kg/m^3), u is wind speed (m/s), u_{max} is the maximum wind speed (m/s) and $F(u)$ is the probability distribution function of the wind speeds.

2. The expected power from a typical turbine ($E(p_t)$) was computed similarly (2), but with limits to represent the turbine power curve (3).

$$E(p_t) = \sum_{u=0}^{u_{max}} 0.5\mathrm{C}_p\rho {u_t}^3 F(u) \qquad (2)$$

$$u_t = \begin{cases} 0, & u < u_{in} \\ u, & u_{in} \le u < u_{rated} \\ u_{rated}, & u_{rated} \le u < u_{out} \\ 0, & u \ge u_{out} \end{cases} \qquad (3)$$

   Where C_p is the coefficient of performance, u_t is the equivalent wind speed for a wind turbine (m/s), u_{in} is the cut-in wind speed (m/s), u_{rated} is the rated wind speed (m/s), and u_{out} is the cut-out wind speed (m/s).

3. A plot was used to compare the cumulative time at all wind speeds between original and synthetic WSTS.
4. The number of transitions between wind speed states for the original and synthetic WSTS was recorded for comparison.
5. To assess the quality of replicating seasonal characteristics two tests were carried out. Firstly, the frequency spectrum of the synthetic WSTS was compared to the original WSTS by using a Fourier Transform. In the spectrum, the frequencies for both WSTS should have similar amplitudes if the seasonal variation has been modelled successfully.
   The second test quantified the occurrence of weather windows. This was computed by calculating the percentage of time a maintenance team could be dispatched. The length of the weather window and the wind speed threshold is dependent on the maintenance type and the travel distance. For this work a wind speed threshold of 10 m/s and a time of 48 hours was taken as a weather window, similar to those found for a jack-up vessel in [3].
6. To assess whether the underlying statistical properties of the wind speed were captured the ACF was computed for an exemplar synthetic WSTS for each modelling technique and the original WSTS.

These 6 criteria produced 7 measurements to be used as a metric to assess synthetic WSTS quality.

c. Synthetic WSTS Production

4 modelling techniques were assessed:

Random sampling from probability distributions (PDF): A daily mean wind speed was calculated by sampling from a Weibull distribution. A normal distribution with mean and variance related to the daily mean wind speed was sampled to synthesise the 10-minute WSTS [5].

Continuous Markov Process: The Markov process uses the transitions between wind speeds in the original WSTS to dictate the transitions occurring in the synthetic WSTS. The next wind speed state is determined by the current state, and the shortest transition time from the current state.

Hidden Markov Process: Similar to the Markov process, but with higher order processes that do not determine the output of the model, but do dictate which lower order states are available at a given time. In this paper the high order processes were used to determine seasonal characteristics and weather windows.

Auto-Regressive (AR(X)) model: An AR(X) model uses the weighted value of the previous X observations in a time series, alongside a randomly generated error term, to determine the next value in the series. In this case a simple third order model (AR(3)) was used.

III. Results

This section summarises the results of the simulations.

Evaluation Criteria {Criterion No.}	Original WSTS	PDF	Markov	Hidden Markov	AR(3)
$E(p)$ (W/m^2) {1}	657.3	678.3 ±9.4	675.8 ± 6.9	669.6 ± 9.2	**646.9 ± 8.9**
$E(p_t)$ (W/m^2) {2}	510.9	491.6 ± 4.8	517.5 ± 3.8	**512.4 ± 5.4**	529.2 ± 5.5
Number of Wind Speed Transitions {4}	19378	4169 ± 18.0	11624 ± 26.9	**15838 ± 29.3**	26139 ± 32.0
Weather Window Opportunities (%) {5}	14.8	24.2 ± 0.6	4.5 ± 0.2	**13.5 ± 0.5**	6.8 ±0.3

Table 1: Results of synthetic WSTS testing against criteria. Best results for each category are in bold.

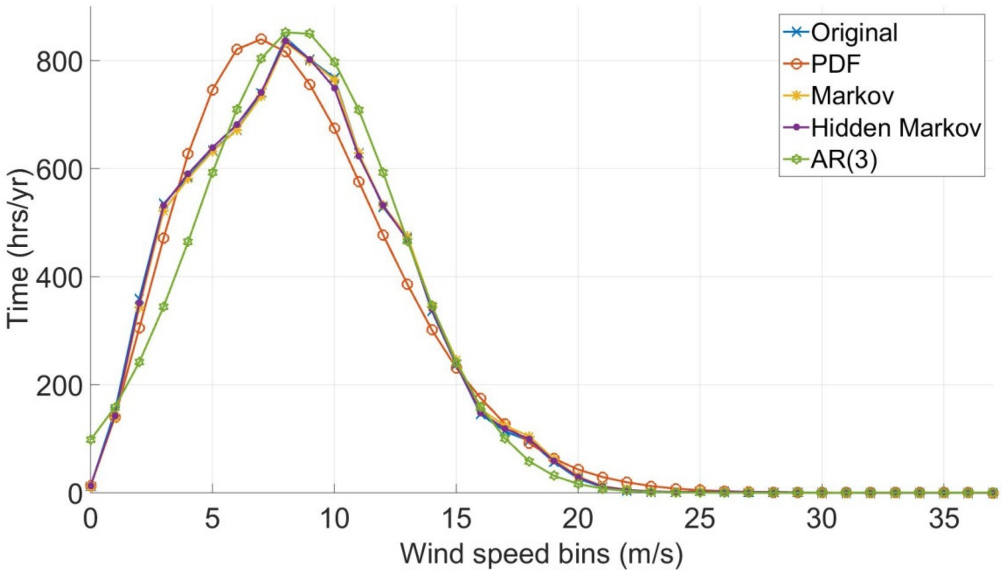

Figure 1: Wind speed mean residence times of original and synthetic WSTS (criterion 3).

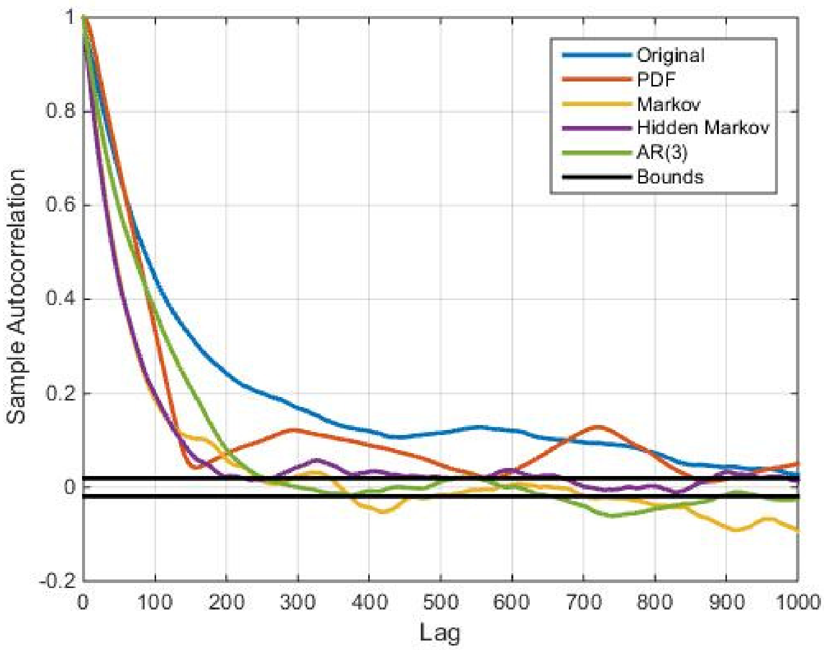

Figure 2: Samples auto-correlation function (ACF) results of original and synthetic WSTS (criterion 6).

From these results, the AR(3) performs best against criteria 1 (Table 1) and 6 (Figure 1), whilst the hidden Markov proves performs best against criteria 2, 3 4 and 5. (Table 1, Figure 2). Therefore, from these results, the most appropriate WSTS simulator for reliability analysis is the hidden Markov process.

However, no modelling technique performs best against all criteria and none capture the ACF as closely as desired. Therefore, there is scope for a more advanced technique for wind speed modelling for reliability analysis. Based on the results detailed, a combination of a more complex AR model for short term modelling and elements of a hidden Markov process for long term seasonal aspects could prove the most appropriate modelling technique.

IV. Conclusion

This work has outlined the desirable criteria of synthetic WSTS for use in offshore wind farm reliability analysis. WSTS simulators were used to produce synthetic WSTS which were compared with these criteria. The most appropriate WSTS simulator for reliability analysis is the hidden Markov process based on the chosen criteria.

V. Learning Objectives

The learning objectives are as follows:

- To understand what characteristics of the wind speed are important for reliability analysis of offshore wind turbines.
- To provide a testing procedure for ensuring WSTS simulators for synthetic WSTS are fit for purpose.
- To determine the most promising modelling techniques of synthetic WSTS for reliability analysis.

VI. References

[1] E. Davey and A. Nimmo. *Offshore Wind Cost Reduction, Pathways Study*. 2012; Available from: http://www.thecrownestate.co.uk/media/305094/offshore-wind-cost-reduction-pathways-study.pdf.

[2] W. Musial and B. Ram. *Large-Scale Offshore Wind Power in the United States: Assessment of Opportunities and Barriers*. 2010; Available from: http://www.nrel.gov/docs/fy10osti/40745.pdf

[3] J. Dowell, et al., *Analysis of Wind and Wave Data to Assess Maintenance Access to Offshore Wind Farms* in *European Safety and Reliability Association Conference* 2013: Amsterdam.

[4] Noordzeewind. *Noordzeewind: Reports & Data*. 2014; Available from: http://www.noordzeewind.nl/en/knowledge/reportsdata/.

[5] B. Kazemtabrizi, C. Crabtree, and S. Hogg, *Reliability Evaluation of New Offshore Wind Farm Electrical Grid Connection Topologies*, in *ASME Turbo Expo 2013: Turbine Technical Conference and Exposition* 2013: Texas, USA. p. 1-10.