IMPACT OF RELIABILITY PERFORMANCE OF WIND POWER SYSTEMS ON ENERGY PRODUCTION

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This paper presents a methodology designated to assess more accurately the energy output of wind power plants. The conventional methodology used nowadays for productivity estimations is replaced by a comprehensive reliability procedure that involves Monte Carlo simulations. Statistics and past recordings of failure rates and repair times of wind turbines in operation constitute the inputs for the proposed procedure. Moreover, up-to-date UK reports are used to define the reliability model of the electricity network which connects the wind system to the grid. The outcomes of the simulation procedure are exploited such that indicators, which quantify the energy production, are addressed.

Keywords: energy yield, reliability assessment, wind power system, wind turbine.

1. Introduction

The attractiveness of governmental incentives redirected the interest of investors towards wind power generation all over the world. Over the last decade, the installed capacity in wind energy increased sharply, reaching 273 GW at the end of 2012 [1]. In order to assure a relatively quick return of investment, wind power plants' stakeholders require accurate pre-feasibility and feasibility surveys. Several factors contribute to the level of accuracy of the reported figures that estimate the payback period of wind power projects. Besides the tariff schemes (i.e., green certificates or feed-in tariffs [2]) promoted in the region the wind power projects are developed, annual energy production plays a significant role in the payback period numbers. Thus, the energy productivity estimations must be as precise as possible.

The objective of this paper is to expand the conventional methodology employed in estimating the wind power systems' energy output and develop a multitask approach applicable not only to (pre-) feasibility studies, but also to planning and operation of wind power systems. The proposed procedure addresses the actual performance of individual machine or whole wind power plant, and computes the energy production with availability/unavailability values obtained from reliability simulations.

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2. Energy output computation

The conventional method used for estimating the energy production of wind power plants is a simple and straightforward procedure if accurate wind speed forecasts are available. Since the methods for long-term predictions of the wind speed at a given site are significantly inaccurate, planning the annual energy production of wind power plants is a difficult task for engineers. Any improvement in the estimations is appreciated as it may increase wind power plant owners' income.

This section briefly presents how the energy generated by wind power plants is nowadays estimated based on the power curve of wind turbines (WTs) and identifies some of its drawbacks. The power curve of a particular WT manufacturer, which is used in this paper, is illustrated in Fig. 1.

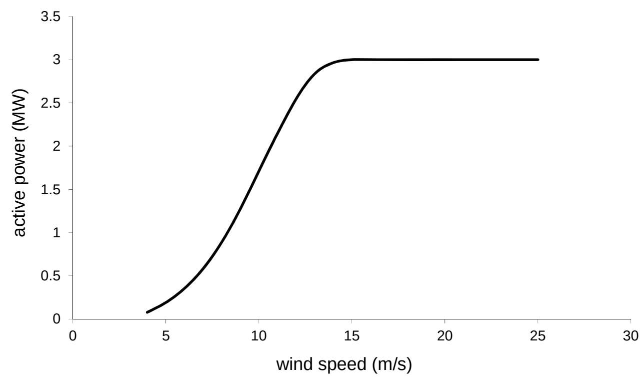

Fig.1. Power curve characteristic of the analysed WT.

Annual on-site wind speed recordings are used to obtain the probability distribution $\mathcal{P}$ of the wind speed w within the cut-in (4 m/s) and cut-out (25 m/s) range of WT as described in [3]:

$$\boldsymbol{\mathcal{P}}(w) = \frac{f_w}{N} \tag{1}$$

where N is the total number of data points within the time interval data has been recorded and f_w is the frequency in hours of each wind speed value that falls in the range of 4 to 25 m/s. The empirical probability distribution of wind speed data can be approximated, if required in further studies, by a theoretical distribution function (e.g., Weibull [3] or Rayleigh [4]) with a given mean value and standard deviation.

Wind speed measurements at a given location are used to build the probability density function (PDF) in Fig. 2 that is employed to assess the energy production of a WT or entire plant. The mean value and standard deviation of the wind speed are 11.41 m/s and 4.08 m/s, respectively.

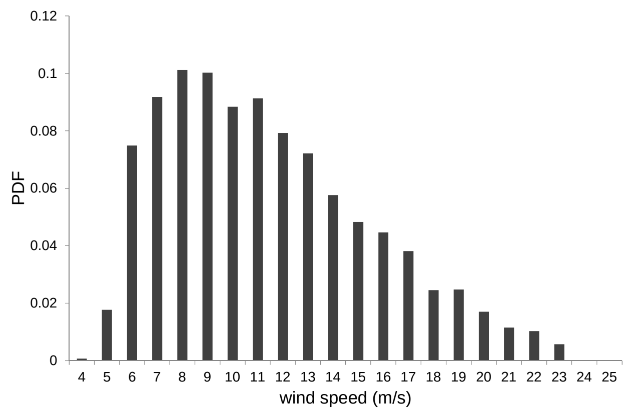

Fig.2. PDF of wind speed data measurements.

Once the empirical probability distribution of wind speed is quantified, the power $p(w)$ corresponding to the wind speed data in the power curve is used to estimate the annual energy production:

$$\boldsymbol{E} = 8760 \cdot \sum_{w=4}^{25} \mathcal{P}(w) \cdot p(w) \qquad \textbf{(2)}$$

Fig. 3 presents the energy yield for a 3-MW WT whose features are in accordance with the aforementioned power curve. Its annual energy output is projected to about 16.64 GWh.

Assumptions that the annual energy production of wind power plants is influenced by the availability of WTs are considered in power plants productivity surveys so as to achieve a more accurate estimation. In the absence of real data, the availability of the machines is considered above 90 % [5]-[7]. These numbers could however lead to unrealistic predictions as the availability of individual machines can in practice drop to 50-60 % [8]. Therefore the reliability performance of individual machine must be included in the algorithm which assesses the energy production of the wind park. In this case, a probability distribution of the wind speed is not enough and a wind speed forecasting model is required so as to predict the wind speed at the time a WT fails to operate. This paper assumes that the forecasting model is available and the wind profile known. Fig. 4 illustrates a sample of the hourly wind speed forecast at the analysed site.

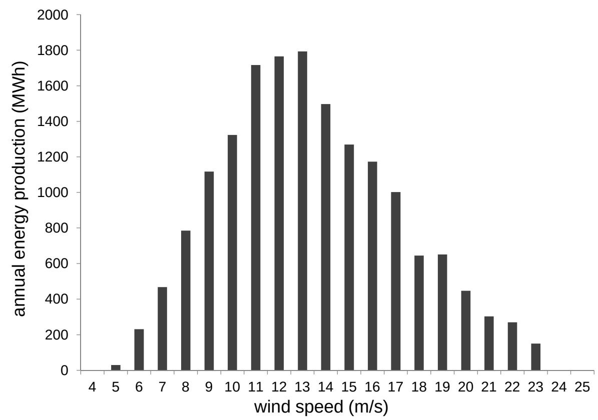

Fig.3. Energy output of a 3-MW WT.

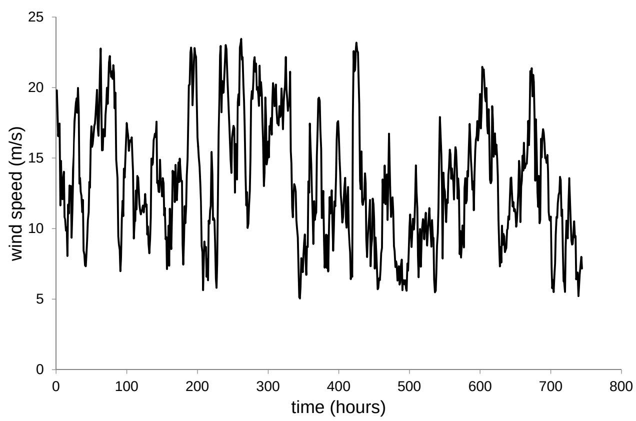

Fig.4. Wind speed forecast for a 30-day time interval.

3. Reliability assessment of wind power systems

The reliability performance assessment of power systems is in general a complex procedure that requires comprehensive knowledge of the system components involved in the analysis. Two common methods often applied in reliability studies are referred to as analytical approaches and simulation techniques [9]. An analytical assessment provides a general characterisation of the parameters/indicators of interest, limiting only to average value and standard deviation outputs. More detailed information, such as the probability distributions in time of some parameters, can be achieved if simulation techniques are addressed instead of analytical methods. Inverse transform method [10], also known as Monte Carlo simulation (MCS), is the method that has frequently been used in the literature to assess the reliability performance of power systems [11] or [12].

The MCS-based method introduced in this paper to increase the accuracy of wind systems' energy yield estimations is a generalisation of the procedure described in [13]-[15]. Firstly, the physical parts of the analysed system are identified and their components with electrical and mechanical parameters are used to build up the reliability model for the MCS procedure. Then, failure rates and repair times are assigned to all power components based on past recordings, if available, or statistics collected from databases with similar equipment in operation in case new installed wind power plants are analysed.

A random generator is defined to assign random variables to an inverse distribution function such that the failure rates and repair times can be converted in operating and failure states of the power components and thus of the whole system. The conventional assumption that exponential distribution is chosen to model the initial conditions of power components' failure rates and repair times is adopted in this paper, although other distributions could be considered as well [16]. The period of time allocated to the reliability analysis to generate failure and operating states for the system is one year and the period of simulation of 25 years corresponds to the average lifetime of all power components. Repeating the procedure for a desired number of simulated years, the reliability performance of individual power components or entire plant expressed as probability distributions can be obtained. Moreover, every time a power component, which can be either a part of the WT or power system up to the interconnection point with the transmission system, fails to operate, the expected energy not supplied (EENS) can be calculated based on the wind profile assumed during the failure state of the component. This means that a correlation between the moments in time when the failure occurs, the duration required to repair the faulted component and the wind speed forecast at the moment during the fault must be implemented in the MCS procedure to better estimate the energy supplied into the grid.

4. Wind power system layout and reliability input data

The wind power plant considered in this paper for the reliability analysis consists of ten 3-MW WTs connected through a radial configuration to the point of interconnection with the transmission system. The layout of the wind park is shown in Fig. 5. Accordingly, two substations are used to deliver the generated power into the grid. Each WT is connected to the medium voltage (MV) substation through a 0.69/33 kV transformer, whereas a 33 kV power cable is the link to the 33/132 kV high voltage (HV) substation.

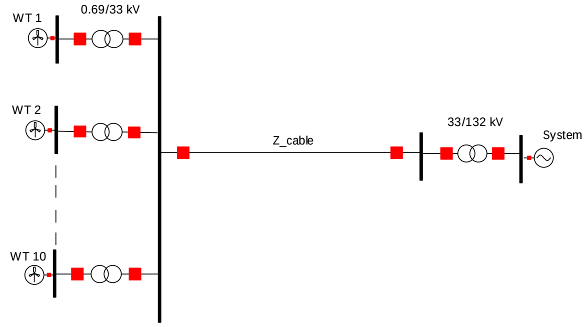

Fig.5. Layout of wind power test system.

The input data for the simulation procedure are selected from a comprehensive database created from reports of WTs in operation [17] and data available in the literature [7], [18] or [19]. Table 1 summarises the failure rates and repair times of main WT components. Furthermore, up-to-date statistics reported by the UK Energy Networks Association (ENA) [20] are used to model the operating and failure states of the network components (i.e., busbars, lines, transformers, etc.) which connect the WTs to grid. These are presented in Table 2.

Table 1

Failure rates and repair times of WT components [7], [17]-[19]

WT component	Failure rate (failures/year)	Repair time (hours)
gearbox	0.47	180
generator	0.40	200
converter	0.04	100
blade/pitch	0.053	75
control system	0.05	35

Table 2

Failure rates and repair times of main network components [20]

Power component	Voltage level (kV)	Failure rate (failures/year)	Repair times (hours)
cables	11	0.091	9.5
	33	0.034	20.5
transformers	0.69/33	0.01	75
	33/132	0.0392	250
busbars	0.69	0.005	24
	33	0.08	140
	132	0.08	140
circuit breakers	0.69	0.005	36
	33	0.0041	52
	132	0.0264	98.4

5. Reliability results

The outputs of the MCS procedure can be expressed as probability distributions of the states the test system in Fig. 5 may experience throughout a period of time. The frequency and duration of outages of individual components, parts of the system or entire system are the main reliability metrics assessed in this paper for quantifying the unavailability and energy output of the wind power plant under analysis.

Figs. 6 and 7 illustrate the results necessary to identify the impact that reliability performance of WTs has on energy production.

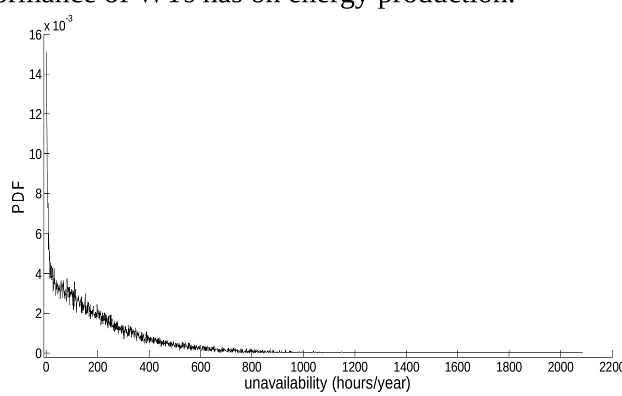

Fig. 6. Unavailability of WT 1 connected to the grid.

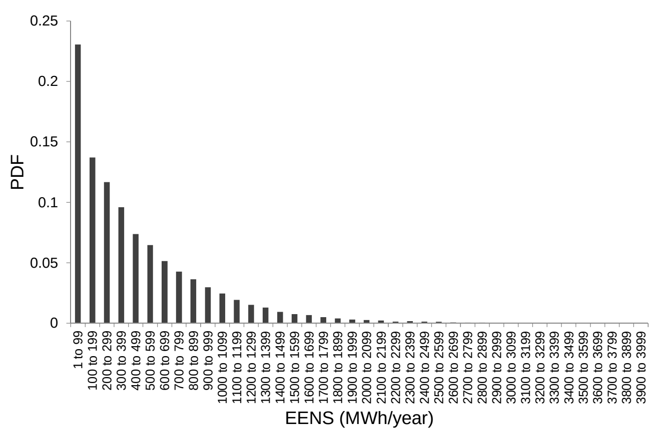

Fig. 7. Expected energy not supplied distribution for a single WT.

The unavailability of a single WT is in average about 200 hours/year and its corresponding EENS index, which is calculated based on the forecasted wind profile, is 458 MWh/year. This means that the WT performance is overestimated when the conventional method described in Section 2 is used to assess the productivity of wind power plants. The annual energy output is estimated at 16.18 GWh, confirming that it is indeed affected by the reliability of the WT. Besides mean values, the PDF results also provide information about the extreme values of the unavailability and energy not supplied indices. Even though those values are unlikely to occur, some events could affect the energy production for up to 2100 hours/year or 4 GWh/year and therefore must be considered in the planning strategies. An annual unavailability of 24 % (or 2100 hours) would reduce sharply the annual energy output from 16.18 GWh to 12.64 GWh.

The abovementioned strategy is extended to further determine the annual energy production of the 10-WT system in Fig. 5. The energy output calculated in the conventional way is the value obtained for a single WT multiplied by the total number of WTs within the wind park. In the case study presented in this paper the annual energy output is estimated to 166.4 GWh. The figures change when the reliability performance of individual machine is considered in the analysis. The estimated energy for the entire wind power plant drops in average by 2.8 GWh/year and sometimes may get to about 94 % of the values reported by the conventional methodology, according to Fig. 8.

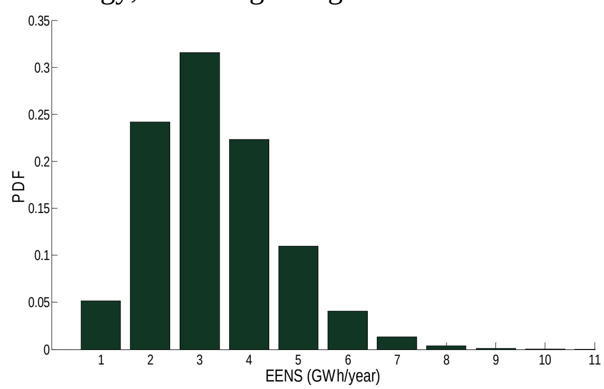

Fig. 8. Estimations of EENS index for the wind power plant composed of ten WTs

The results of interest for the productivity characterisation of a single WT and entire wind power plant are gathered in Table 3. An interesting outcome is emphasised by the variation in the reliability metrics provided by the MCS procedure. An average availability of 98 % obtained for a single machine is sustained amongst the general output of the entire power plant, whereas significant variations occur in the extreme values. The minimum energy output of a WT is characterised by a drop in the availability, which gets to 76 %. Nevertheless, this extreme value is balanced to 94 % in case an overall system reliability assessment is performed. The discrepancies between the results of a single WT and those of the whole plant can be explained by some events that occur rarely in the system and not all WTs within the wind park experience them.

That is why some studies report very high availability of WTs, while others consider poor reliability of the machines [8]. Therefore, assumptions of random availability values (e.g., 5 or 10%-step interval variations) should be avoided and the reliability performance of individual WTs must be assessed in order to avoid overestimations of wind power plants productivity.

Table 3

Summary of calculated energy-related indicators

Index	Estimations performance					
	without reliability		with reliability			
	single WT	entire plant	single WT		entire plant	
			mean	extreme	mean	extreme
Energy (GWh)	16.64	166.4	16.18	12.64	163.6	156
Availability (%)	100	100	97.7	76	98.3	93.7

6. Conclusions

This paper has discussed the possible impact that the reliability performance of WTs may have on the energy production of a single unit or entire system. A wind power plant composed of ten 3-MW WTs has been engaged in the analysis carried out in the paper. The energy output estimations obtained with the conventional methodology, which is nowadays used in industry, are compared against the outcomes of the proposed reliability procedure. The initial results reported here show that more accurate predictions can be achieved if a proper reliability algorithm is involved in the productivity assessment. Rare events, which usually are not captured by the conventional techniques, may increase the unavailability of a WT from an average value of 2 % to 24 %. The risk of missing those events increases if an overall reliability assessment is preferred to an individual one. This means that any detail counts in the reliability analysis and sensitivity analyses must be carried out when particular aspects are of interest.

R E F E R E N C E S

[1]. *** The World Wind Energy Association, Half-year report, 2012.

[2]. *I.-S. Ilie*, Energy policy assessment in competitive market conditions, MSc thesis, University Politehnica of Bucharest, Feb. 2008.

[3]. *A.N. Celik*, "Energy output estimation for small-scale wind power generators using Weibull-representative wind data", in Elsevier Journal of Wind Engineering and Industrial Aerodynamics, **91**, 2002, pp. 693-707.

[4]. *H.T. Mengelkamp*, "On the energy output estimation of wind turbines", in International Journal of Energy Research, **vol. 12**, no. 1, Jan/March 1988, pp. 113-123.

[5]. *M. Zhao, Z. Chen and F. Blaabjerg*, "Generation ratio availability assessment of electrical systems for offshore wind farms", in IEEE Trans. on Energy Conversion, **vol. 22**, no. 3, Sept. 2003, pp. 755-763.

[6]. *J. Nilsson and L. Bertling*, "Maintenance management of wind power systems using condition monitoring systems-life cycle cost analysis for two case studies", in IEEE Trans. on Energy Conversion, **vol. 22**, no. 1, March 2007, pp. 223-229.

[7]. *M. Boettcher and F.W. Fuchs*, "Power electronic converters in wind energy systems-considerations of reliability and strategies for increasing availability", in Proceedings of the 14th European Conf. on Power Electronics and Applications, Birmingham, UK, Aug./Sept. 2011, pp. 1-10.

[8]. *I.S. Ilie, P. Di Leo, F. Spertino and G. Chicco*, "Protections impact on the availability of a wind power plant operating in real conditions", in Proceedings of IEEE PowerTech Conference, Bucharest, Romania, June/July 2009, pp. 1-7.

[9]. *R. Billinton and R.N. Allan*, Reliability evaluation of power systems, Plenum Press, New York, 1996.

[10]. *R.Y. Rubinstein*, Simulation and the Monte Carlo method, John Wiley & Sons, New York, 1981.

[11]. *A. Sankarakrishnan and R. Billinton*, "Sequential Monte Carlo Simulation for Composite Power System Reliability Analysis with Time Varying Loads", in IEEE Trans. on Power Systems, **vol. 10**, no. 3, August 1995, pp. 1540-1545.

[12]. *M.R. Bhuiyan and R.N. Allan*, "Modelling Multistate Problems in Sequential Simulation of Power System Reliability Studies", in IEE Proc. Gen., Trans. and Distrib., **vol. 142**, no. 4, July 1995, pp. 343-349.

[13]. *R.N. Allan and R. Billinton*, "Power system reliability and its assessment. Part 1: Background and generating capacity", in Power Engineering Journal, **vol. 6,** no. 4, July 1992, pp. 191-196.

[14]. *R.N. Allan and R. Billinton*, "Power system reliability and its assessment. Part 2: Composite generation and transmission systems", in Power Engineering Journal, **vol. 6**, no. 6, Nov. 1992, pp. 291-297.

[15]. *I.-S. Ilie, I. Hernando-Gil, A.J. Collin, J.L. Acosta and S. Djokic*, "Reliability performance assessment in smart grids with demand-side management", in Proceedings of IEEE PES Conf. on Innovative Smart Grid Technologies, Manchester, UK, Dec. 2011, pp. 1-7.

[16]. *R. Billinton and P. Wang*, "Teaching distribution system reliability evaluation using Monte Carlo simulation", IEEE Trans. on Power Systems, vol. **14**, no.2, May 1999, pp. 397-403.

[17]. *B. Hayes, I.-S. Ilie, A. Porpodas and S. Djokic*, "Equivalent power curve model of a wind farm based on field measurement data", in Proceedings of IEEE PowerTech Conference, Trondheim, Norway, June 2011, pp. 1-7.

[18]. *J. Ribrant and L.M. Bertling*, "Survey on failures in wind power systems with focus on Swedish wind power plants during 1997-2005", in IEEE Trans. on Energy Conversion, **vol. 22**, no. 1, March 2007, pp. 167-173.

[19]. *F. Besnard, K. Fischer and L. Bertling*, "Reliability-centred asset maintenance-a step towards enhanced reliability, availability and profitability of wind power plants", in Proceedings of the IEEE PES Conference on Innovative Smart Grid Technologies, Gothenburg, Sweden, Oct. 2010, pp. 1-8.

[20]. *** Energy Networks Association (ENA) - National Fault and Interruption Reporting Scheme, National system and equipment performance, Report, December 2010.