ANALYSIS OF THE POWER OUTPUT OF A WIND TURBINES CLUSTER IN THE GUADELOUPEAN ARCHIPELAGO

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This article presents the result of an experimental investigation of the wind speed − power output transfer function of a Squirrel Cage Induction Generator (SCIG) wind turbines cluster in the Guadeloupean archipelago. The analysis shows that the fluctuations of the power output and the wind speed are correlated only for time scales larger than 8 minutes. A probabilistic transfer function, based on the conditional cumulative distribution function of the power output, given the mean wind speed, is also presented. It gives a synthetic view of the dispersion of the aggregated power output.

Keywords: wind energy, power curve, wind variability

Introduction

Throughout the last two decades, wind energy has become a common component for electricity generation in many energy systems [1-4]. Wind energy is currently the world's fastest growing renewable power source. In Europe, the wind energy installed capacity has grown 600 % between 1997 and 2003. Wind energy with 60 TW·h, already represents 2.3 % of European electrical energy consumption [1]. Worldwide, wind energy capacity rises from 4,800 MW in 1995 to 73,904 MW at the end of 2006 [3]. The technological evolution of wind energy conversion systems has been fast. Today, conventional wind turbine's rated power often exceeds 2 MW, almost ten times the rated power of a state of the art wind turbines fifteen years ago [5].

Although wind energy is often described as an unreliable energy source because of its variability, it can be argued however, that many component of a power system (both on the supply and on the demand side) are indeed variable and some drawbacks can be hardly predictable [1, 6]. Moreover, wind energy is not the only electrical network component that varies with the meteorological conditions: the electrical demand is also dependent on the weather; a heat wave may induce consumption peak, a thermal power plant may be affected by a thunderstorm, tree falls on power lines can cause sudden interruptions of supply.

Network operators have long experience in dealing with variability within the power system; they have, routinely, to cope with changeable demand and unanticipated transmission and power generation breakdown.

Efficient forecasting scheme based on a better knowledge of the wind variations characteristics along with their influence on power output variation is of key importance for the optimal integration of wind energy in power system. It is the uncertainty of the forecasts that cause balancing difficult, not the variability of the wind power [7]. Numerous studies have been devoted to wind power forecasting [8-16]. Hourly averaged wind speed data variations can be predicted to a great extent [13].

Concerning the wind speed to electrical power conversion, many studies have investigated wind turbines response to wind variations. Under the influence of meteorological conditions wind speed fluctuates over time. These variations occur on different time scales: from seconds to years. The response of a wind turbine, in term of power output variations, depends on the wind turbine technology [5, 17-19]. Some smoothing effect can also be obtained due to the turbine inertia and size. For a group of turbines; further smoothing can be expected due to the spatial distribution of the turbine within the area. For large area, wind energy overall variability can be much lower than the variability of a single wind turbine since the meteorological fluctuations do not affect each wind cluster at the same time [1].

To anticipate for wind power variability is even more crucial for island power system management. Their small size and the fact that they are not connected to large utility network impose supplementary constraints to wind power integration. In the Guadeloupean archipelago (French West-Indies), by the end of 2006, the total installed wind energy capacity reached 21 MW. Moreover, wind power can already contribute up to 5 % of the instantaneous electricity consumption. At this level, wind energy contribution can be equivalent to the current network primary control reserve. Increasing wind power penetration rate could make it necessary to provide some warranty on wind power production in order to optimize the conventional back-up capacity intended to palliate wind production shortages.

The common approach to investigate wind farms power output is based on wind measurement within the site. Often, a single point wind speed measurement campaign is used to assess the site's wind power potential. However, the electrical power variations observed for a wind farm are the consequences of the actual wind variations as seen by each wind turbine as well as the electricity network shortcomings and the various maintenance problems that may affect the wind turbines efficiency. Therefore, it is necessary to complete the power curve obtained for the group of wind turbines with a probabilistic approach that gives for a specified wind speed range, the distribution of the expected wind farm power output.

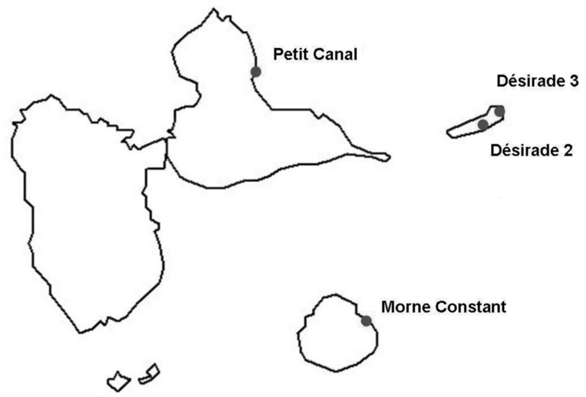

Fig. 1. *Schematic view of the Guadeloupean archipelago; the dots point to the location of the major wind turbines clusters*

In this article, we present the result of an experimental investigation of the wind to power output transfer function of the larger wind cluster of the Guadeloupean archipelago. This wind turbine cluster consists of 32 SCIG (Squirrel Cage Induction Generator) wind turbines positioned at the top of a sea cliff at Petit-Canal, on the east coast of Guadeloupe (see location on Fig.1).

The proposed analysis is based on an experimental data set that consists of wind speed and electrical power output samples measured simultaneously during a one and a half year measurement campaign within the wind farm site.

The wind energy production site

The measurement campaign was conducted at the wind energy production site of Petit-Canal in Guadeloupe Operated by the Vergnet Caraïbes Company (Fig. 1). The wind turbines are provided by the Vergnet Company and have been designed to resist wind speed intensity of more than 200 km/h. The turbines are mounted on 60 m masts that can be lowered, in case of a major hurricane, with an attached motorized hosting gear. They can be promptly dismantled and laid on the ground. No particular equipment is needed for their installation.

These wind turbines are fixed speed Squirrel Cage Induction Generator (SCIG). Therefore, their rotational speed is dictated by the electrical grid frequency (in Guadeloupe the grid frequency is 50 Hz). Consequently, at the lower end of its wind speed operational range the turbine rotates too fast, and at the higher end it rotates too slowly in respect with its optimal angular speed. Therefore, the SCIG operates below its maximum efficiency at most wind speeds. Nevertheless, the SCIG technology is proven to be robust and cost-effective. The rotor blades are rigidly fixed to the hub and are designed to stall for wind speed above 25 m/s. The stalled regulation is intended to limit the rotor angular speed in case of high wind speed.

Experimental set up

The measurements were carried out during one year and a half from December 2003 to June 2005. Wind speed and direction along with the wind turbines cluster electrical power output were collected during this measurement campaign. The wind speed V_{wind} was measured, in a horizontal plane, with a three-cup anemometer (model A100L2 from Vector Instruments). The anemometer was mounted on a 40 m (131 ft) tall mast erected 20 m (66 ft) from the cliff edge, at 38 m (125 ft) from the ground. The response time of the anemometer is 0.15 s. This remains compatible with a sampling rate of 1 Hertz for the sake of a statistical analysis of the wind speed variations. Table 1 gives the specifications of both the anemometer and the wind vane.

Table 1

Anemometer and wind vane specifications

	A100L2R	**W200P**
Size	Height = 200 mm; Diameter = 55 mm; Weight = 350 g	Height = 270 mm; Diameter = 56 mm; Weight = 350 g
Supply Voltage	12 V (6,5 V to 28 V)	5 V (20 V max)
Materials	Anodized aluminium, stainless steels and ABS plastics for all exposed parts	
Range of Operation	Threshold: 0.15 m/s; starting speed: 0.2 m/s; stopping speed: 0.1 m/s; Max. wind speed: 75 m/s	Max. Speed: > 75 m/s; range: 360° mechanical angle Accuracy: ±2° obtainable in steady winds over 5 m/s (3.5° gap at North)
Analogue Output	Calibration: 0 to 2.500 V DC for 0 to 75 m/s (32,4 mv per m/s).	0 to 5 V for 0° to 360°
Response Time	150 ms first order lag typical	

The electrical power of a cluster of 32 wind turbines was measured simultaneously with the wind speed; a power-to-volt converter was used to gauge the electrical power. In this paper, the electrical power $P_{cluster}$ is expressed as a percentage of the total power capacity of the wind turbines cluster.
The measured data were downloaded to a PC connected to the RS232 port of a Campbell Scientific CR23X data logger. This data acquisition system was set-up to operate continuously and the PC can be administrated via a phone line, which allows a remote control of the data acquisition operation. The data analysis is performed using the Matlab® software package.

Wind velocity and electrical power Fourier analysis

A one week sample of wind speed and electrical power signals are plotted in Fig. 2 and Fig. 3. Both signals exhibit variations on various time scales. On large time scales (larger than 1 hour), the temporal behaviour of V_{wind} and $P_{cluster}$ are almost similar as seen on Fig. 4 where the 1-hour-moving-average wind speed and power output are plotted. But for the shortest time scales, the two signals exhibit different behaviour.

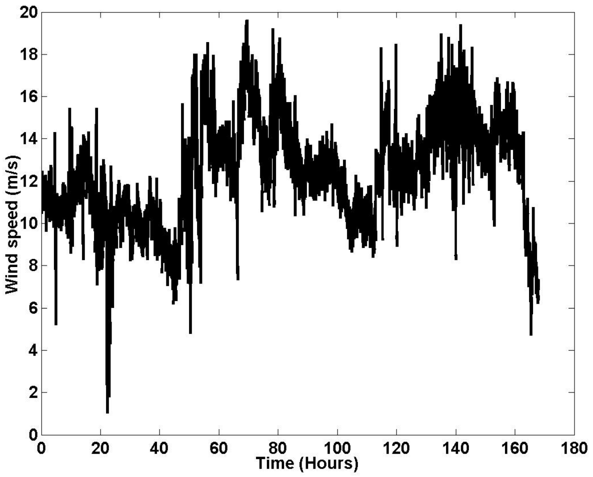

Fig. 2. *One week sample of wind speed*

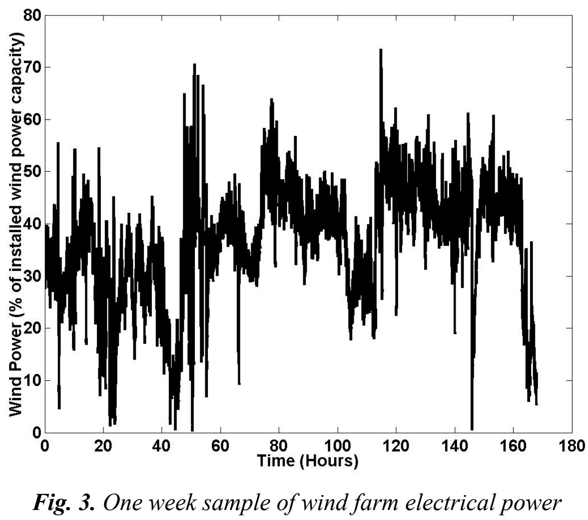

Fig. 3. *One week sample of wind farm electrical power*

To go further into the investigation of the wind speed – electrical power relationship for the short time scales, we use various tools from the Fourier analysis. The plots in figure 4 are the power spectral density of both V_{wind} and $P_{cluster}$. The spectra are plotted for the frequency range between 1/2 hours ($1.3 \cdot 10^{-4}$ Hz) and 1/1 minutes ($2 \cdot 10^{-2}$ Hz) using the periodogram method. Within this frequency range, no frequency peak can be observed from the two spectra. Moreover, we calculated the magnitude square coherence between the wind velocity V_{wind} and the power signal $P_{cluster}$. The magnitude square coherence is defined by:

$$C_{VP}(f) = \frac{\left|P_{vp}(f)\right|^2}{P_{vv}(f)P_{pp}(f)}.$$

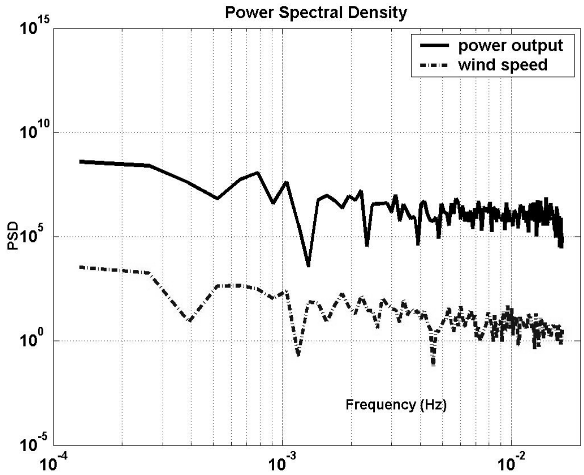

Fig. 4. *Power spectral density of the wind speed and the wind cluster power output*

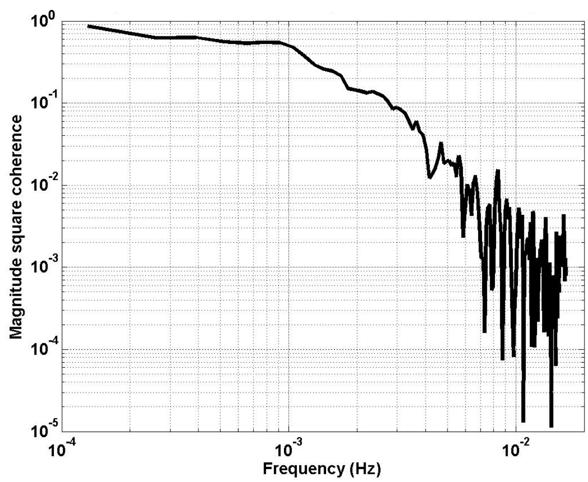

Fig. 5. *Magnitude square coherence between wind speed and electrical power as a function of wind oscillations frequency*

It is equal to the cross spectrum of V_{wind} and $P_{cluster}$ divided by the product of the power spectra of V_{wind} and $P_{cluster}$. This quotient is a real number between 0 and 1 that measures the correlation between V_{wind} and $P_{cluster}$ at the frequency f. The plot of Fig. 5 shows the coherence C_{VP} to drop below 0.2 for frequency above 1/8 minutes ($2 \cdot 10^{-3}$ Hz). This indicates the coherence between wind speed and power fluctuations associated with time scales lower than 8 minutes are low (frequencies larger than $2 \cdot 10^{-3}$ Hz). The plot of the magnitude square coherence is completed by the plot of the gain of the wind speed (V_{wind}) – wind turbine cluster electrical power output ($P_{cluster}$) transfer function. The transfer function is the quotient of the cross spectrum of v and $P_{cluster}$ and the power spectrum of V_{wind}. The gain of this transfer function, plotted in Fig. 6, drops by more than 10 dB below its maximum value (obtained for large time scales) for frequencies larger than 1/8 minutes ($2 \cdot 10^{3}$ Hz). The phase of the transfer function, plotted in Fig. 7 remains close to zero for frequencies below $2 \cdot 10^{3}$ Hz. From both the magnitude square coherence and the transfer function plots, one can deduce that on large time scales, power variations are well correlated with wind speed variations; the large time scales wind variations affect the whole wind farm almost simultaneously. On the other hand, the variations on the short time scales of the power output are not correlated with those of the wind speed.

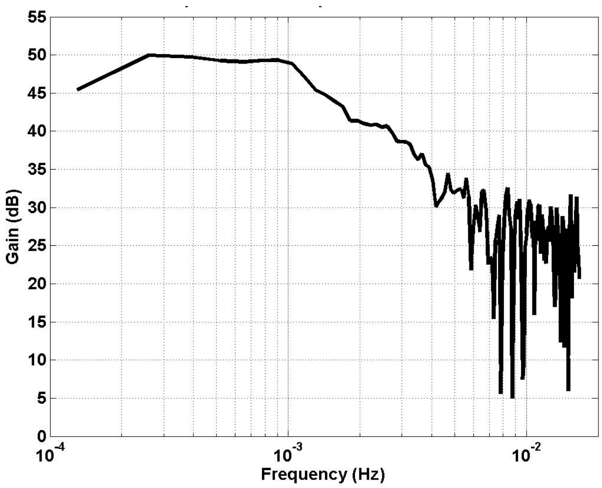

Fig. 6. *Gain of the Transfer Function between wind speed and electrical power as a function of wind oscillations frequency*

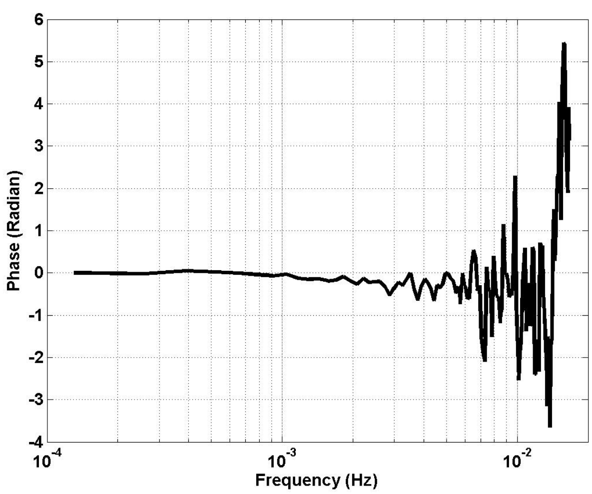

Fig. 7. *Phase of the Transfer Function between wind speed and electrical power as a function of wind oscillations frequency*

Wind velocity and electrical power statistical analysis

So far we have investigated the response of the wind cluster to wind variations in term of frequency response. In this section, we examine the distribution of the wind cluster power output $P_{cluster}$ and its relation with the wind speed. The power generated by a wind turbine is a function of both the properties of the wind and the turbine electromechanical characteristics. For a wind cluster, the power output also depends on the turbines scattering within the production site. In Fig. 8, the 10 minutes averaged power output $\overline{P}_{cluster}$ is plotted versus the 10 minutes averaged wind speed $\overline{V}_{wind}$. This plot displays a cloud of points, thus showing evidence that the mapping between the electrical power and the wind speed is not a bijective function.

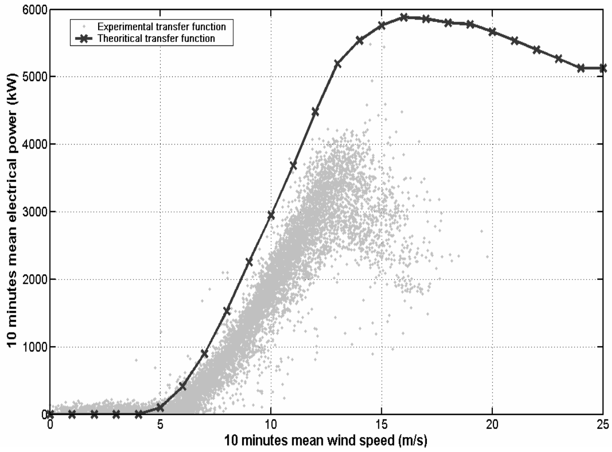

Fig. 8. *10 minutes averaged power versus wind speed*

The theoretical power curve of the wind turbines cluster, obtained by considering that each wind turbine is affected by the same wind speed and operates simultaneously, is also plotted in Fig. 8. The theoretical power curve remains greater than the clouds of points except for low mean wind speed value. The observed dispersion of the power output highlights:

1) The existence of turbulence on wind energy production site. The site faces the wind along the coast line on approximately 2 km. It is likely that the wind turbines are not affected by the same wind.

2) The variation in the number of wind turbines actually available. Maintenance operations can require shutting down one or several wind turbines, in that case, the aggregated power capacity is reduced.

3) The unsteady meteorological conditions that induce fast wind speed fluctuations.

Another way to represent this wind to power mapping is to consider the conditional probability that the observed mean electrical power $\overline{P}_{cluster}$ takes on a value less than or equal to a given threshold P, given a mean wind speed $\overline{V}_{wind}$. This conditional probability is the conditional cumulative distribution function noted

$F\left(P|\overline{V}_{wind}\right) = prob\left(\overline{P}_{cluster} \le P|\overline{V}_{wind}\right)$ and is expressed in percentage. In Fig. 9, the iso-percentages of the function $F\left(P|\overline{V}_{wind}\right)$ are plotted in the $\left(\overline{V}_{wind}, P\right)$ plane for an averaging time equal to 10 minutes. The value of the threshold P is expressed as a fraction of $P_{capacity}$.
Also in Fig. 9, we have plotted three power curves associated with 60 %, 50 % and 40 % of the installed power capacity of the turbines cluster. For mean wind speed between the cut-in wind speed and 10 m/s, the actual power output stays below the 60 % power curve. For mean wind speed ranging from 10 m/s to 14 m/s, the actual power output varies mainly between 40 % and 60 % of the cluster's capacity. For wind speed large than 14 m/s, the wind output decrease faster than the theoretical power curves as the mean wind speed increases. Works is continuing to better characterise and understand the wind turbines cluster behaviour.

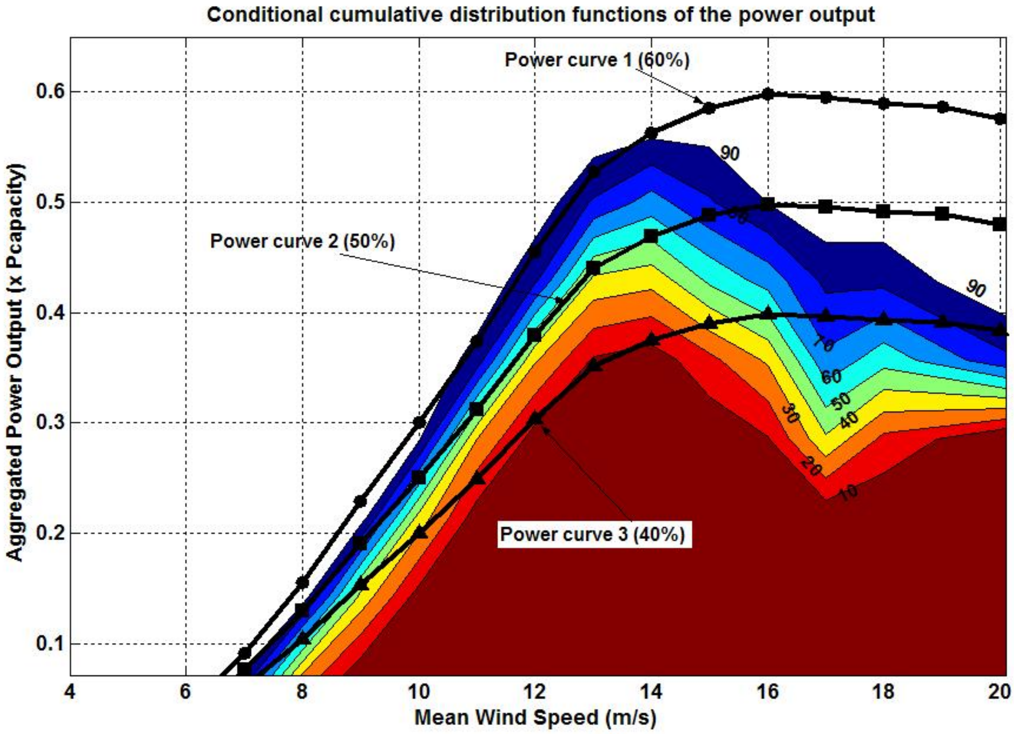

Fig. 9. *Conditional cumulative distribution functions of the wind turbines cluster power output plotted along with 60, 50 and 40 % power curve*

Conclusion

This paper presents the first experimental results of an investigation of the wind speed to power output transfer function of a wind turbines cluster in Guadeloupe (FWI). A first approach, based on Fourier analysis, shows that the fluctuation of the cluster's power output is correlated to those of the wind speed only for time scales larger than 8 minutes. For short time scales, the two signals are not correlated. In order to evaluate the actual production of a wind farm, we have plotted the conditional cumulative distribution of the electrical power provided by a SCIG wind turbines cluster, given the mean wind speed. This plot gives a quantitative view of the power output dispersion. During the measurement campaign, the probability to have the 10 minutes averaged electrical power to take on a value larger than 50 % of $P_{capacity}$ equals 11 %. This probabilistic transfer function gives a practical estimation of the electrical power produced by a cluster of wind turbines as a function of the mean wind speed. Future works should address the unsteadiness of this map throughout the year.

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