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Abstract. In order to implement accurate models for wind power ramp forecasting, ramps need to be previously characterised. This issue has been typically addressed by performing binary ramp/non-ramp classifications based on ad-hoc assessed thresholds. However, recent works question this approach. This paper presents the ramp function, an innovative wavelet-based tool which detects and characterises ramp events in wind power time series. The underlying idea is to assess a continuous index related to the ramp intensity at each time step, which is obtained by considering large power output gradients evaluated under different time scales (up to typical ramp durations). The ramp function overcomes some of the drawbacks shown by the aforementioned binary classification and permits forecasters to easily reveal specific features of the ramp behaviour observed at a wind farm. As an example, the daily profile of the ramp-up and ramp-down intensities are obtained for the case of a wind farm located in Spain.

1. Introduction

Nowadays, large-scale wind power integration is conditioned to properly manage large and fast power output variations (ramp events) observed at wind farms and portfolios. Short-term wind power forecasting is expected to play an important role by developing new strategies oriented to reduce wind power uncertainty during these specific events [1, 2]. In this regard, locating ramp events within a wind power time series is important because it allows forecasters to regard meteorological processes and operational states of the wind farm in the proper time periods when analysing ramp causes. Thus, a poor characterisation of the ramp performance is likely to hinder the identification of the processes that cause ramp events. To this end, a binary ramp definition is usually adopted by setting threshold values related to the absolute power variation and the time duration of the event observed in the wind power time series. These thresholds are usually defined ad-hoc and may vary substantially from one study to another. Actually, several works agree on the lack of a robust ramp definition [3, 4, 5, 6]. Furthermore, the binary approach has been called into question because it may artificially lead to a reduced performance of a ramp forecasting model [2, 5].

In this work, the ramp function is introduced as a means of characterising the ramp performance of a wind power time series [7]. The underlying idea is that a ramp event is characterised by high power output gradients evaluated under different time scales. The ramp function is based on the discrete wavelet transform and it provides a continuous index related

to the ramp intensity at each time step. This permits to overcome several drawbacks related to the use of a binary definition.

The reminder of the paper is structured as follows: section 2 gathers most of the binary ramp definitions reviewed in the literature and some of the related drawbacks are outlined. The ramp function is defined in section 3. Section 4 provides an analysis on how the ramp function can be employed to characterise the daily profile of the ramp intensity. The paper closes with the main conclusions.

2. A review on the ramp event binary definition

The term ramp event refers to a large variation in wind power output that is observed on a wind farm (or in a portfolio) within a short period of time (up to a few hours). In order to detect ramp events within wind power time series, two thresholds are usually adopted concerning the variation in power output and the time period in which this variation takes places. These thresholds are referred to as magnitude, ΔP_0, and duration, Δt of the ramp event. The magnitude threshold is usually expressed as a percentage of the rated power, P_R. Table 1 shows some of the thresholds employed in the literature together with the project size (when provided).

Table 1. Thresholds for wind power ramp definition reviewed in the literature.

| Author	ΔP_0	Δt	P_R
Cutler (2007) [3]	$75\% P_R$	3 h	65 MW
Cutler (2007) [3]	$65\% P_R$	1 h	65 MW
Truewind (2008) [4]	$15 - 20\% P_R$	1 h	Not spec.
Potter (2009) [2]	$10\% P_R$	1 h	~1 GW
Greaves (2009) [5]	$50\% P_R$	4 h	3-240 MW
Barbour (2010) [8]	$20\% P_R$	30 min	~200 MW
Collier (2010) [9]	$50\% P_R$	4 h	Not spec.
Bradford (2010) [6]	$20\% P_R$	1 h	Not spec.
Bossavy (2010) [10]	$50\% P_R$	n/a	Not spec.
Kamath (2011) [11]	$10 - 12\% P_R$	30 min	~1 GW
Kamath (2011) [11]	$15 - 20\% P_R$	1 h	~1 GW
Gallego (2011) [12]	σ_g	1 h	33 MW
Bossavy (2012) [13]	$30\% P_R$	n/a	8 MW

P_R stands for the rated power of a wind farm or portfolio.

σ_g is the standard deviation of the first-difference of the wind power time series, $\{p_t - p_{t-1}\}$.

This variety of definitions is probably due to the fact that the risk associated to a large wind power ramp depends on end-user considerations. Thus, there is no reason why one definition should dominate over others. However, the use of a binary definition entails several shortcomings, such as the fact that the frequency of ramp events observed may become very sensitive with respect to the mentioned threshold values. Additionally, the use of a binary classification (ramp/non-ramp) implies that ramp events are identified with no distinctions on their characteristics. This fact supports the notion that ramps are similar to one another even if ramp events are usually observed with different magnitudes or durations.

The mentioned drawbacks are illustrated in figure 1. This figure shows the ramp performance based on some of the aforementioned binary definitions for the case of a wind farm located in Spain with a rated power of $P_R = 24.5$ MW. Specifically, those time steps labelled as ramp events

that would change their status if ΔP_0 is increased by $5\% P_R$ are highlighted with red circles. The ramp function (to be defined in section 3) is also shown. It can be seen that the ramp-up event observed on 28/Apr is captured by all the binary criteria. However, disagreements among them are observed during the strong gradients experienced between 29/Apr and 1/May. In addition, what can be considered a ramp event from a binary point of view may become highly conditioned to the precise threshold value selected, as shown by the red circles in the figure. Conversely, the ramp function provides a means to compare the ramp intensity of two different events without forcing a binary decision on their ramp/non-ramp nature.
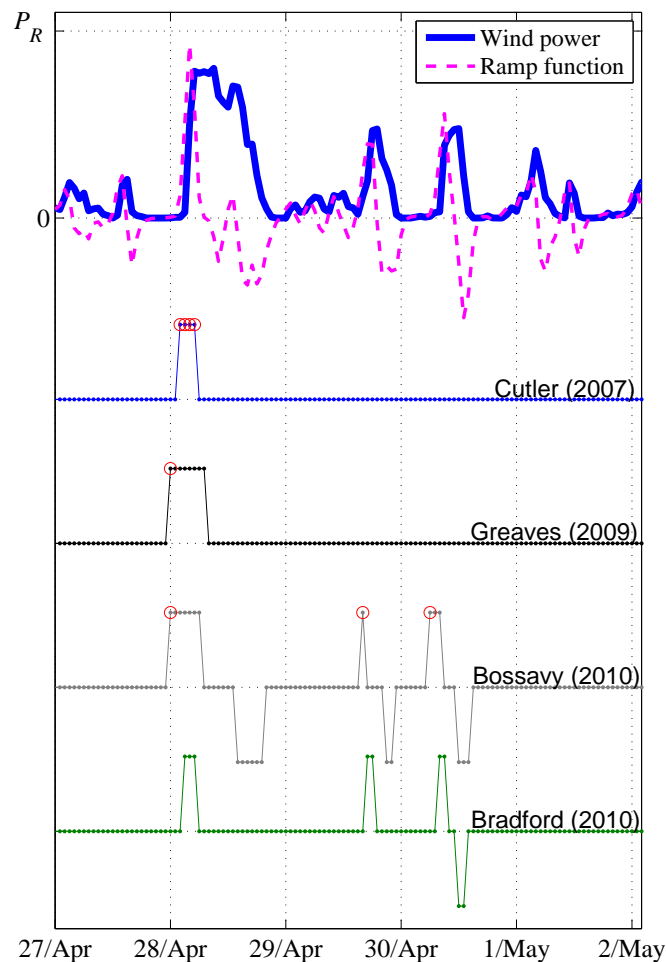
Figure 1. Wind power time series (blue full line) together with the ramp function (magenta dashed-line) and four binary ramp classifications (below) based on different definitions of a ramp event (see table 1). The ramp function corresponds to the case of $\lambda_1 = 2$ and $\lambda_N = 5$ (see next section). Time periods labelled as ramp events that would change to non-ramp by considering an amplitude threshold increased by $5\% P_R$ are highlighted with a circle.

3. The ramp function

Ramp events represent local events in a wind power time series and are characterised by sharp variations in power. Despite the fact that the magnitude and duration may vary from one ramp to another, the essential concept of a ramp is that a certain large gradient is maintained during consecutive time steps of the time series.

The Wavelet Transform (WT) is a mathematical technique that permits the analysis of the time-frequency content of a signal. By using a specific wavelet function, a one-dimensional time series is mapped into a two-dimensional set of coefficients providing information on both the location and the scale of specific events. In particular, the WT based on the Haar function provides information about the gradient experienced by the signal at different time scales [14].

The coefficients of the WT based on the Haar wavelet, $W_H^{t,\lambda}$, of a certain wind power output time series $\{p_t\}$ are given by:

$$
W_H^{t,\lambda} = \begin{cases} \frac{1}{\sqrt{\lambda}} \cdot \left(\sum_{j=1}^{\lambda/2} p_{t+j-1} - \sum_{j=1}^{\lambda/2} p_{t-j} \right) & \text{, if } \lambda \text{ is even} \\[2em] \frac{1}{\sqrt{\lambda}} \cdot \left(\sum_{j=1}^{(\lambda-1)/2} p_{t+j} - \sum_{j=1}^{(\lambda-1)/2} p_{t-j} \right) & \text{, if } \lambda \text{ is odd} \end{cases}, \tag{1}
$$

where λ relates the time scale considered to evaluate the gradient experienced by $\{p_t\}$ (the minimum λ value being $\lambda_{min} = 2$ because at least two power records are needed to evaluate the gradient). Figure 2 shows the coefficients $W_H^{t,\lambda}$ obtained through equation (1) during a four days period where ramp events were reported. It can be seen that ramp events are clearly identified by intense vertical lines, reflecting that large gradients are observed under several time scales.

The labour of characterising the ramp performance of a wind power time series can take advantage of the mentioned feature in a simple way by defining the ramp function, R_t, as the addition of the wavelet coefficients $W_H^{t,\lambda}$ for the interval of scales λ given by $[\lambda_1, \lambda_N]$:

$$
R_t(\lambda_1, \lambda_N) = \sum_{\lambda=\lambda_1}^{\lambda_N} W_H^{t,\lambda}. \tag{2}
$$

By performing this computation, $\{R_t\}$ becomes related to the sharpness of the ramp events because it gathers at each time step the contribution of the gradient evaluated under different time scales.

The choice for the range of time scales $[\lambda_1, \lambda_N]$ permits to customise to some extent the notion of ramp event for a particular case study. For the case of λ_1, it is reasonable to set $\lambda_1 = \lambda_{min} = 2$ because it represents the minimum time scale at which the power gradient can be evaluated. On the other hand, λ_N represents the highest time scale to be considered. For the case of hourly wind power time series, reasonable values for this parameter are in the range of 4 to 8. It was demonstrated in [7] that values within this range permit the ramp function to highlight ramp events with durations up to five hours.

4. The daily profile of the ramp intensity

One of the advantages of characterising the ramp performance by means of a continuous index is that statistical analysis can be readily performed to reveal specific features of the ramp behaviour observed at a wind farm. As an example, the daily profile of the ramp intensity is here explored. Findings about the ramp diurnal pattern are relevant since they may give insights about the ramp underlying meteorological processes. For example, ramp events systematically observed
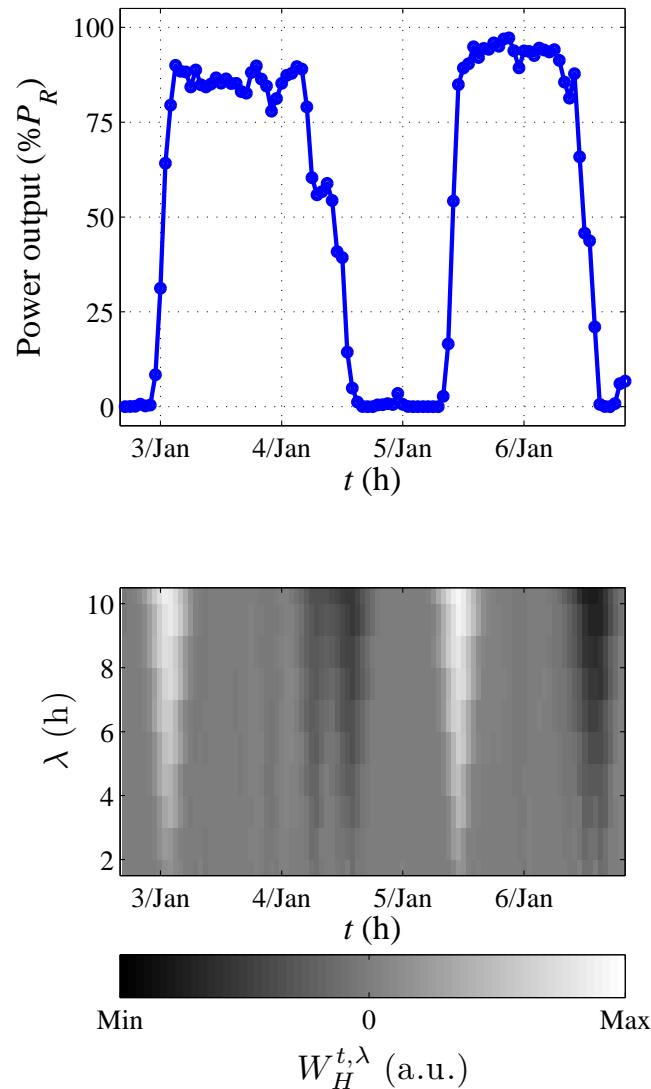
Figure 2. Top: wind power output during a four days period. Bottom: coefficients of the wavelet transform based on the Haar function, $W_H^{t,\lambda}$. "a.u." stands for arbitrary units.

in certain hours may suggest that convective processes with a diurnal cycle (such as sea-land breezes in coastal placements) might be playing a key role in causing these events.

The ramp function time series, $\{R_t\}$, can be re-scaled by defining the relative ramp function time series, $\{r_t\}$, as follows:

$$r_t = \frac{R_t}{\max(|R_t|)}. \tag{3}$$

By doing this, $\{r_t\}$ provides ramp indexes in the range of -1 to 1. Figure 3 shows the statistical distribution of $\{r_t\}$ conditioned to the hour of the day. Only positive indexes (related to ramp-up

events) have been considered on the left graph whereas the distribution of the negative indexes (ramp-down events) are shown on the right graph. The statistical distribution is characterised in terms of quartiles. It can be observed that the second quartile (the median, plotted with full lines) scores values close to zero for every hour. Dashed lines show first and third quartiles (Q1 and Q3) as a function of the hour of the day, showing that the ramp function is below the 20% of its maximum for the 50% of the time. Likewise, dash-dot lines represent the maximum and the minimum values to not be considered outliers. This border is given by 1.5 times the interquartile range, IQR, defined as $IQR = Q3 - Q1$.[1] Thus, these maximum and minimum values are given by $Q3 + 1.5 \cdot IQR$ and $Q1 - 1.5 \cdot IQR$, respectively. Finally, outliers (extreme events) are shown individually by means of circles. It can be seen that large ramp-up events were very seldom observed in afternoon hours (from H12 to H18) as it is interpreted from the absence of circles related to high ramp indexes within these hours. Conversely, large ramp-down events seemed to be distributed evenly along the day. Nevertheless, the area limited between Q1 and the minimum may suggest that moderate ramp-down events were likely to happen specially at noon. It is also worth to point out that the differences observed among the distributions suggest, as it could be expected, the different nature of the processes involved in ramp-up and ramp-down events.
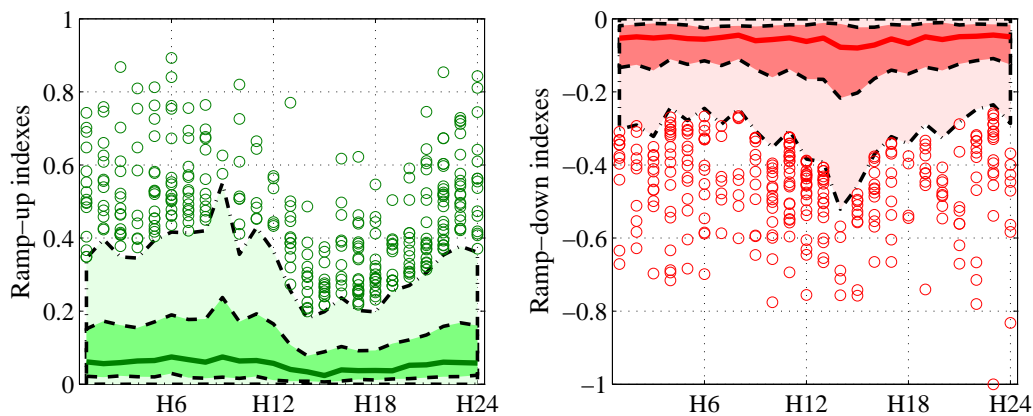
Figure 3. Statistical distribution of the ramp function conditioned to the hour of the day for the case of ramp-up events (left) and ramp-down events (right) (results based on one year data). —— median, − − − first and third quartiles, — · — minimum and maximum (extreme events excluded), ∘ extreme events.

5. Conclusions

In this paper we present the ramp function, an innovative approach to detect and characterise ramp events in wind power time series. The main feature of this approach is that the ramp intensity is obtained by considering large power gradients evaluated under different time scales. The range of time scales considered is established by means of a parameter which permits to customise the notion of ramp event to particular study cases. The characterisation of the ramp performance is deemed suitable since it permits to overcome some of the drawbacks related to the binary ramp/non-ramp classification approach. In particular, the relation between the ramp intensity and the hour of the day was analysed concluding that, for the particular case study

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[1] The limit of $1.5 \times IQR$ is usually employed in box-and-whisker diagrams.

considered, ramp-up events occur seldom in afternoon hours, whereas moderate ramp-down events are likely to happen specially at noon. Finally, further research could be conducted in order to explore potential relationships between ramp events and potential explanatory variables provided by Numerical Weather Prediction models and SCADA systems, which may contribute to a better understanding of wind power ramp causes

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