Impact of Weather Regimes on the Wind Power Ramp Forecast.

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Abstract

The stochastic nature of wind and the continuous need to balance electric generation with demand poses serious challenges to the power system operators. The impact of large wind integration into the power system is mitigated by decreasing the uncertainty associated with wind forecasts. In particular, the forecast of severe wind power ramps is important due to its impact on the energy market and grid operation and planning.

This study proposes to classify the weather regimes over continental Portugal associated with the severe wind power production ramps. Thus, an automated classification system is developed by combining principal components analysis and k-means clustering to find the most representative atmospheric flow patterns near the surface. This system can tackle with the synoptic spatial variability allowing the decrease of phase and timing mismatches present in single time forecasts. Then, the patterns are linked to the wind power production. Results show that it is possible to associate weather regimes with different levels of wind power production and identify certain atmospheric circulations with a higher chance to trigger severe wind power ramps.

Keywords: ***Wind power Forecast, Ramps Events, Synoptic classification, Power smoothing.***

1 Introduction

Wind power installed capacity in Portugal increased at high rates in recent years and became one of the major renewable energy sources. In 2012, wind power was the major renewable energy source (50.2% of renewable production) exceeding hydro power plants production (32.3% of renewable production) and representing 20% of the total electrical supply [1].

From an environmental and economical view, the growth of wind power installed capacity in the power system brings beneficial impacts: it lessens the carbon emissions drawn from the carbon-fuel electricity generation and reduces its fuel costs [2]. However, because of the fluctuating nature of wind power, negative impacts can arise bringing new challenges for the transmission system operator (TSO), especially for large-scale integration [3]. As described in [2], one of the main challenges regards the variability of wind power within 1-6 h, where the TSO need to assess current and future production values to make real-time decisions. As is well known in the sector, if the wind power production fails to produce at the predicted power level due to reduced wind intensity, fast-responding units such as thermal or hydro power plants are needed to achieve the demand level. Thus, wind power production forecast plays an important role [4, 5], especially through periods of increased rapid changes, known as “ramps events”. There is no clear standard definition of wind power ramps in the literature [6], which poses some difficulty on assessing this events.

The literature of short-time wind energy forecasting is beyond the scope of this paper, however detailed reviews may be found in [6, 7]. The common approach is based on a single time-series forecast that can be obtained from probabilistic models [8], numerical weather prediction models (NWP) or by combining both [7]. In general, these approaches have two types of errors: amplitude and phase [7, 9]. These errors could be reduced by providing spatial NWP forecast information to the TSO [10] because NWP models allow to forecast how the large-scale transient synoptic phenomena (e.g. high pressure displacements or frontogenesis systems) influence near-surface wind. However, its accuracy depends on the weather [11].

On wind power ramps, identifying synoptic circulation patterns can provide a valuable tool to understand the forcing mechanism of regional atmospheric variability. Therefore, the identification and classification of the atmosphere climate states and their daily and intraday wind variability is important [3] because severe wind power fluctuations may be strongly correlated with certain weather regimes (WR). For example, the evolution of certain transient regimes could be linked to higher changes of large ramp events.

There are only a few studies that highlight the meteorological situation associated to severe fluctuations of wind power production. The main physical triggers of wind power ramps are credited to cold fronts, low-pressure systems and troughs [12, 13]. These authors used a manual identification of the synoptic situation. However, recent studies [14, 15] in the wind speed variability can be useful to provide an automated identification. Commonly, this approach is based on principal components analysis (PCA) coupled with clustering analysis (CA). This method has been successfully applied in different applications such as precipitation [16], summer fires [17] and strong wind events [14] in the Euro-Atlantic region, where the relationship with the large-scale atmospheric circulation is strong.

The main aims of this study are: a) the automated identification and classification of atmospheric flow patterns near the surface in Portugal Continental; b) create a short-time forecast tool of severe wind power ramps, which can act as a warning for the TSO. Section 2 of the paper provides a brief background on relevant weather phenomena. Section 3 describes the input data and the statistical method developed based on PCA and CA techniques. Section 4 presents the results obtained. Finally, in section 5 some conclusions are provided.

2 Large-scale atmospheric description

At this point, it is important to describe the main characteristics of large-scale atmospheric circulation in the Euro-Atlantic region. The atmospheric synoptic circulation is influenced by seasonal migration of the mid-latitudes weather circulation systems. During winter it moves downwards to low latitudes, allowing the passage of warm and cold fronts and other baroclinic synoptic perturbations moving eastward from the Atlantic Ocean [18]. In the summer, the variability is not closely related to large-scale circulation and is dominated by the subtropical high pressure centered in Azores. The high pressure system persists through several days and its intensity varies according the daily cycle of heating and cooling of land surface, a phenomenon known as thermal low [19].

3 Data and Methodology

3.1 Data

From a TSO perspective, the main interest is the forecast of severe ramps in the total national (or in a common control zone) aggregated wind generation rather than ramps from a single wind farm or turbine. It is well documented that aggregating wind farms with a wide geographical dispersion enable the statistical smoothing effects, thus mitigating the fast power fluctuations and reducing forecast errors [3]. However, for some atmospheric large-scale events such as cold fronts, the smoothing effects are not observed. So, the aggregated national wind power production series for continental Portugal during 2009 and 2010 [20] was used. The dataset also allows to associate the temporal scale of severe fluctuations to synoptic variability time scale. The wind power generation time series (with a resolution of 1 hour) were normalized according the wind power installed capacity at end of each month.

The ramp events were detect through visual inspection based on five parameters: growth rate, minimum and maximum power, ramp length and direction. Ramp direction is essential for the TSO due to its impact on the commitment of reserves [21] and the different technical and economic impact of short-term prediction of ramp-down and ramp-up events (e.g. a ramp-down event is more important for the TSO than a ramp-up). In a wind ramp-down event, the TSO needs to compensate the demand with other power plants, requiring the commitment and dispatch of fast starting generating units, usually at a very high reserve cost. On the other hand, an extreme wind ramp-up event, where the total production exceeds the demand, it is possible to curtail wind power to a feasible and adequate level.

Synoptic data information was obtained from an NWP in real-time mode operation. NWP have a good capability of forecast how the large-scale synoptic phenomena (e.g. frontogenesis systems) influence near-surface wind. The NWP model MM5 [22] was used in this work, to provide the 6h time horizon deterministic forecast, during 2009 and 2010. The MM5 forecasts were executed four times a day using the initial and boundary conditions at 00 UTC, 06 UTC, 12 UTC and 18 UTC from the National Centers for Environmental Prediction operational Global Forecast System model output [23], with a horizontal grid spacing of 1°x1°. The numerical experiment setup was configured for recording data every hour in three domains using a two-way nesting technique with spatial resolutions of 81x81km, 27x27km and 9x9km (Figure 1). For all domains, a vertical grid with 26 irregular sigma layers was considered. The vertical structure of the sigma layers was tuned to concentrate more sigma levels in the lower levels. The model results were extracted for the 0.991 sigma level, at approximately 70 meters a.g.l..

3.2 Methodology

The weather circulation type classification assumes a greater dominance in studies where synoptic variability is of major influence [24]. For instance, from geostrophic approximation is recognized the pressure gradient as the driving force on the wind speed in the low surface. Note that a classification method is an approximation [24] because the atmospheric circulation is a continuous system rather than a set of multiple weather types well distinguished.

The automated classification system proposed in this work was based on the combination of a principal component analysis (PCA) with the k-means clustering algorithm. The weather regimes are identified from an unsupervised classification of the NWP hourly forecasts. Later, they will be associated with the severe fluctuations found in the wind power generation.

A circulation-to-environment [24] approach was used, i.e., first an hourly weather classification is performed taking in account several meteorological variables (e.g. wind speed – circulation variable). After, the classification is linked to the wind power production (environment variable). This approach allows to generalize the classification, especially for phenomena with more than one associated synoptic structure [25].

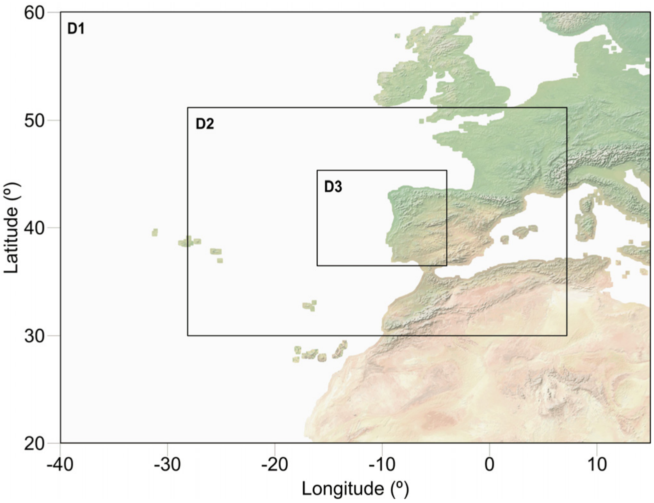


Figure 1. The three nested domains for the MM5 simulation (D1 – 81km; D2-27km and D3 – 9 km).

The use of PCA allows to identify the dominant spatial-temporal variability patterns directly from data by cancelling smaller uncorrelated local effects. Before the application of the PCA to the variables from a grid field (derived from NWP model for every hour) it is required a normalization step, where each variable in each grid point is subtracted of its mean value and scaled by its standard deviation. The covariance matrix is estimated using the normalized data-set and its eigenvectors are computed and sorted based on the descending eigenvalue magnitude. The number of principal components (PC) retained is determined by the North test criteria [26]. As a side effect, the PCA allows to reduce the data-set dimensionality to a computationally manageable figure.

Based on the PCA reduced data-set (scores), a cluster analysis is applied to find and divide the samples according their similarity. The objective is to group the synoptic data that show similar characteristics on the same cluster and separate them from other different groups [24]. In this study, k-means clustering is used to collect the data into weather regimes groups. This problem is computational difficult (NP-hard); however, there are efficient heuristic algorithms that converge quickly to a local optimum. Upon the selection of a k number of clusters, Lloyd's algorithm [27] starts from an initial set k centroids and computes the distance of all the observations to each centroid. The data are assigned to the k clusters by selecting them according with the minimum distance. The k-th centroid is updated by computing the local mean using only its observations. The algorithm iterates until the within-cluster sum of squares is minimized. Although the algorithm converges, it is not possible to prove that the solution is the global optimum and thus the final solution depends of the initial centroid values. Despite the subjectivity in the exact definition of the cluster centers, experience shows that it is possible to have a consistent classification for most of the data. The suitable number of clusters was achieved evaluating the sum of the point’s distance to the centroid. This is, nevertheless, a subjective selection and should be always established according to the purposes of the classification. In the present study the methodology adopted was to preserve the two most representative clusters for each hourly classification, to get a reduced number of clusters with a physical meaning.

4 Results and discussion

4.1 Weather Regimes

The analysis starts by the visual examination of the meteorological weather and surface pressure charts to identify the common synoptic structures associated with the previous detected ramps events to understand which meteorological variables can be addressed as potential triggers. In winter, most of the severe ramp-up events are linked to the upcoming low pressure systems and frontal zones with the convergence of wind speed in Centre/North of Portugal. Figure 2 shows the high values of correlation in the region. Strong ramp-down events are associated with the low pressure centers as they moves inland and pass over the wind farms, driving the wind speed to close zero near the system center. During summer, ramp events are less severe and mainly caused by thermal low intensification. Thus, it can be concluded that: 1) seasonality has a great influence on the occurrence and severity of wind power ramps, being the most severe on the winter due to the low pressure systems; 2) the synoptic variability associated to mid-latitude weather circulation systems and the geographical distribution of the installed wind power capacity with high concentration in the Centre and North of Portugal may explain the slightly larger wind power fluctuations for countries such as Portugal and US, in contrast to those experienced in Nordic countries [2].

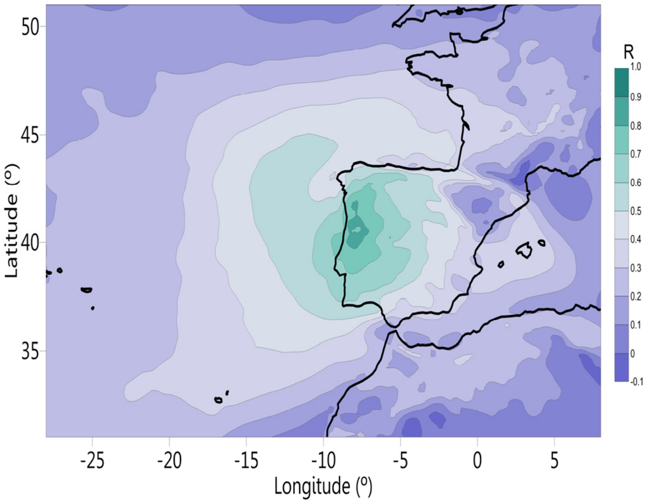


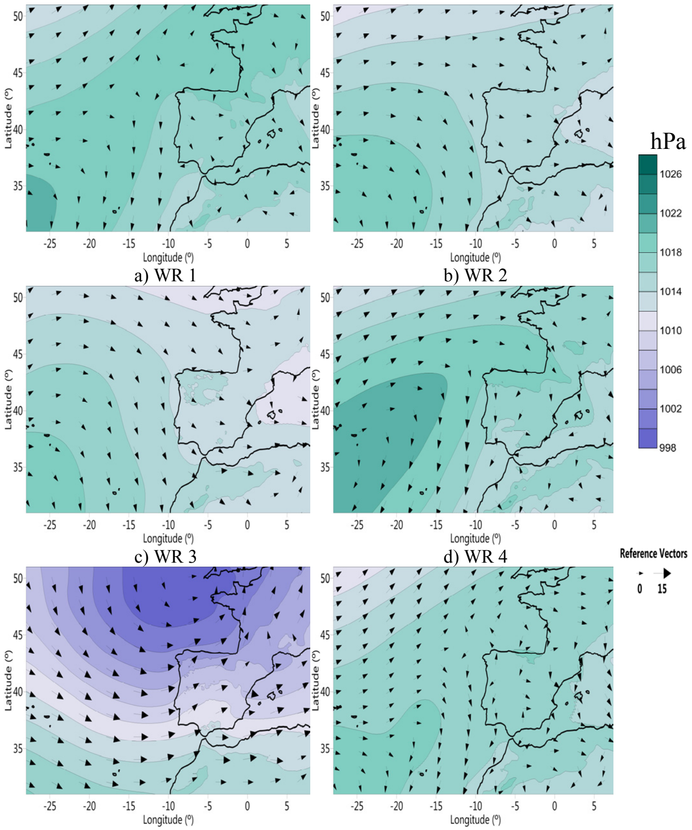
Figure 2. Correlation map between the wind velocity (based on hourly forecast data) for each grid point in the 27 km domain and the wind power production series, for the 2009-2010 period.

Based on the this analysis, the meteorological variables used as predictors to define the weather patterns in the automated classification are: wind velocity; atmospheric stability, computed with the vertical gradient of equivalent potential temperature for two sigma levels; and, the pressure gradient, by applying a first-order centered finite difference approximation to mean sea level pressure field.

A sensitivity test was also performed on the horizontal grid dimension and geographical domain, for the three nested domains. Based on these tests, the 27 km domain was chosen since it covers the synoptic centers with the highest influence on the final results [14] and preventing NWP error amplification, common in high resolutions grids [28].

The application of the proposed automated classification system allows to identify six clusters that represent typical weather regimes. Figure 3 shows a composite plot with the mean sea level pressure and wind speed vector fields, for each weather regime (cluster).

The annual frequency of every weather regimes is represented in the figure 4. A brief description of each cluster and the main characteristics are presented in Table 1



a) WR 1 b) WR 2 c) WR 3 d) WR 4 e) WR 5 f) WR 6

Figure 3. Composite fields of mean sea level pressure (hPa) and wind speed vectors (m/s) associated with each weather regime.

4.2 Linking Weather Regimes with Aggregated Wind Production

In figure 5, a boxplot of wind power production associated with each weather regime is presented. It shows the wind power production in Portugal coupled with the different weather synoptic conditions. WR 1 and 6 are linked with low wind energy production, while WR 5 is associated with high levels of production.

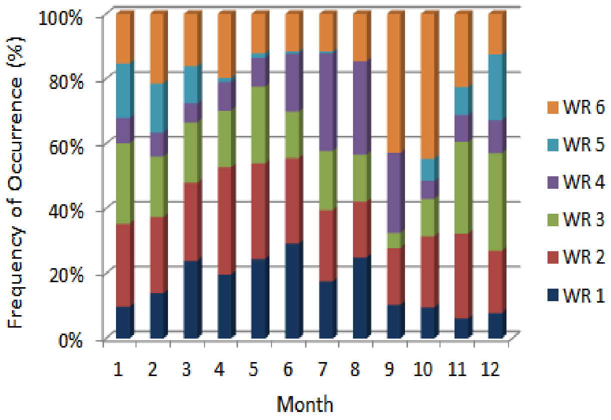


Figure 4. Monthly frequency of the six weather regimes.

TABLE 1. METEOROLOGICAL CHARACTERISTICS OF EACH CLUSTER.

Weather Regime	Main Characteristics
1	High pressure system over the Atlantic Ocean that extend from Azores anticyclone to Northwest of the Iberian Peninsula (IP) and is associated with weak pressure gradient over Portugal, more typically in spring and summer.
2	Zonal dipole pressure system. Absence of significant pressure gradients over the area under study. In the winter, it precedes the forthcoming of a low pressure system and is equality distributed along the year.
3	Meridional dipole pressure system with convergence of strong winds over IP. During winter it is associated with the upcoming of strong low pressure systems, while in the summer it is linked with days with a stronger thermal low. Its frequency is roughly constant throughout the year, with a smaller influence during autumn.
4	Azores anticyclone extends along the Atlantic, with moderate pressure gradient over the north of Portugal, with Eastern and Northeast flow. This weather regime is representative of a summer condition.
5	Large deep low pressure system, associated with strong pressure gradients over the north of IP, further common in the winter.
6	Synoptic pattern similar to cluster 4, however it triggers a weaker flow from North over Portugal. Mostly found in early autumn.

On average, the remaining weather regimes show significant wind power production levels although with a higher dispersion. This can be attributed by the different influences of these WR during the annual cycle.

To evaluate the hourly classification the two clusters associated with each identified ramp event were analyzed. Results, depicted on figure 6a) and 6b), show the correlation between wind power ramps and specific WR sequences:

- Severe ramp-up are associated with the following WR sequence 2(3) – 3(5) – 5(3);
- Severe ramp-down are associated with 5(3) – 3(5) – 2(3);
- For ramp-up until 60% of wind production capacity the sequence is typically 1(2) – 2(3) – 3(2);
- Slow ramp-down tend to be associated with 3(5) – 2 (3) – 2(6).

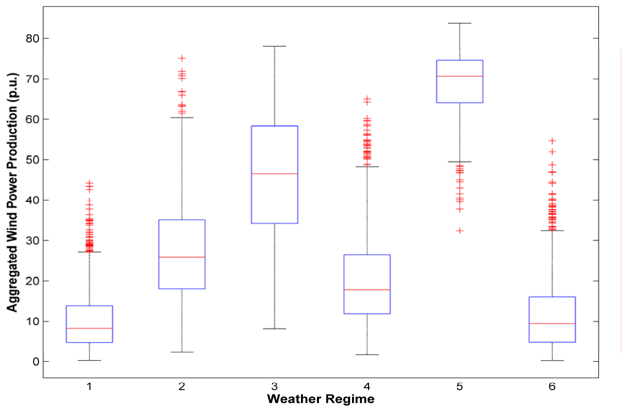


Figure 5. Boxplot of wind power characteristics in each weather regime.

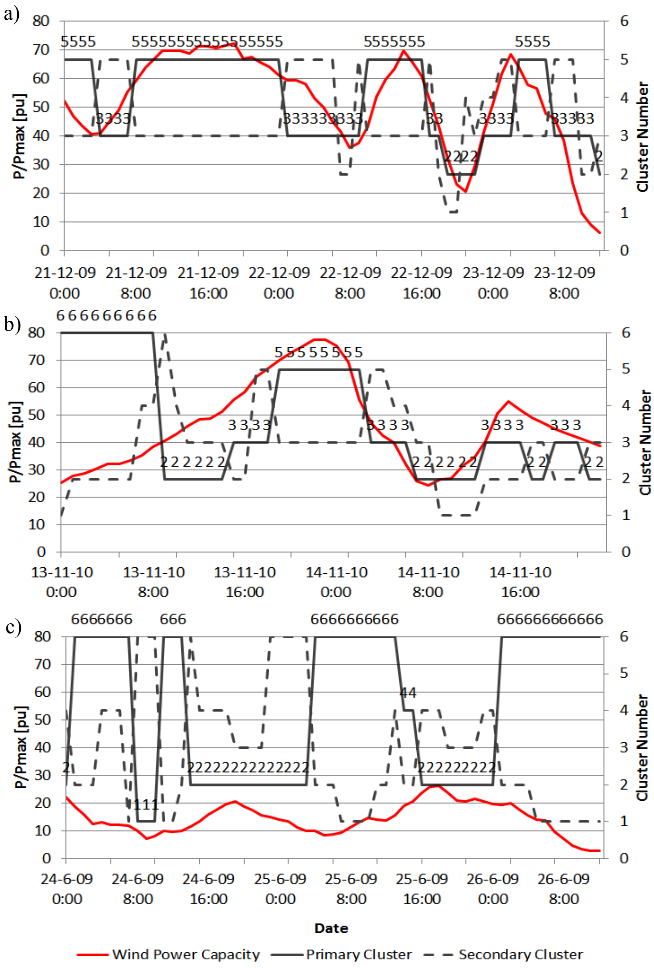
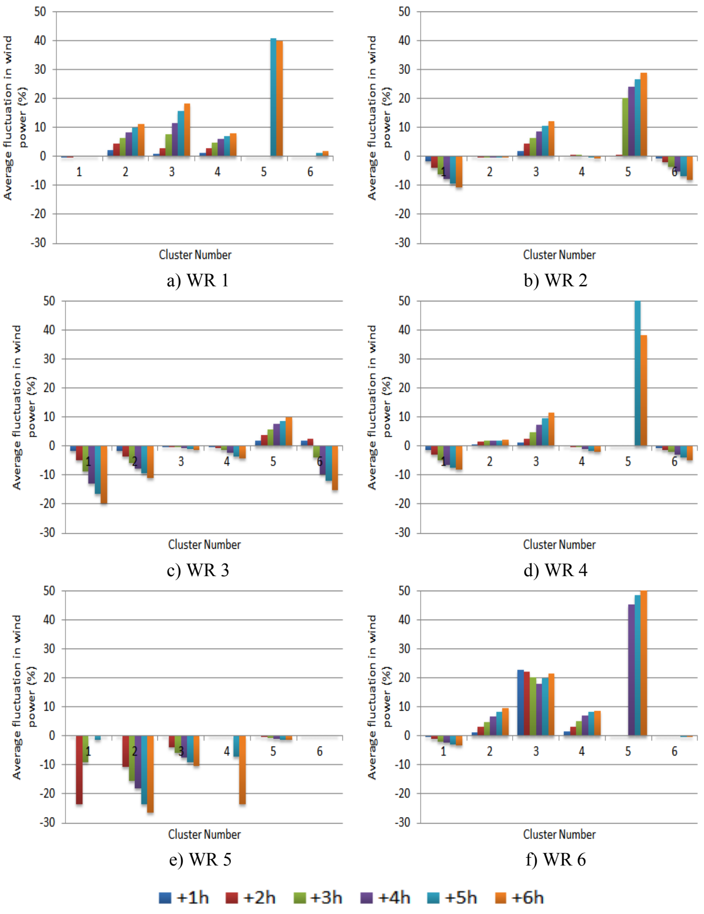


Figure 6. Example of weather pattern classification.



a) WR 1 b) WR 2 c) WR 3 d) WR 4 e) WR 5 f) WR 6

Figure 7. Average changes in wind power production for each WR in within 1-6 hour time horizon taking as reference the diferent weather regimes.

Through this method it is also possible to identify others sequences of weather regimes, for instance, 1(6) – 6(1) – 2(6) associated with weaker fluctuations in the wind power production: figure 6c).

The joint analysis of the WR instances (figure 3) and the variability of wind power for a 6 hour time horizon allow to estimate the average wind power production ramp. Figure 7 shows the variability within each WR. The most severe ramp-up events are characterized with an average ramp of more than 40 % of total capacity installed and are originated (and may be detected) in transitions from: WR6 to WR5; WR4 to WR5; and, WR1 to WR5, with a time-lag of three hours. Significant ramp-down events were identified after two hours of transitions from WR 5 to WR1. The results obtained can also provide the average variations threshold in the production, assisting the TSO in the system management.

5 Conclusion

This paper proposes the identification and characterization of large-scale synoptic circulation associated with wind power production, with special emphasis on fast power fluctuations, aka wind power ramps. The emphasis was on the development of an automated classification methodology based on multivariate statistics (PCA and K-means clustering) with data provide from a NWP in real-time operation.

The results showed that it was possible to determine the synoptic atmospheric circulation patterns with high probability of trigger strong wind power ramp events, opening the possibility for the development of a TSO's warning system.

Further information can be provided through the analysis of average changes in wind power production for each weather regime (see figure 7) and consequently, enabling to keep the component of the reserves' commitment due to wind variability at minimum values, thus reducing wind integration costs. In this sense, for instance, the approach of low pressure systems (WR 5), most common in the winter, poses one of the major challenge because are associated in average with a significative decrease of wind power production. Although further research is needed, the main added value of this work is the use of large-scale circulation information, usually well simulated in NWP that allows to mitigate the amplitude and phase errors associated to a single point forecast. This information may be very useful to TSO and can be coupled with statistical approaches, to improve the short-time wind power forecast.

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