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Index for wind power variability

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Abstract— **Variability of large scale wind power generation is dependent on several factors: characteristics of installed wind power plants, size of the area where the plants are installed, geographic dispersion within that area and its weather regime(s). Variability can be described by ramps in power generation, i.e. changes from time period to time period. Given enough data points, it can be described with a probability density function. This approach focuses on two dimensions of variability: duration of the ramp and probability distribution. This paper proposes an index based on these two dimensions to enable comparisons and characterizations of variability under different conditions. The index is tested with real, large scale wind power generation data from several countries. Considerations while forming an index are discussed, as well as the main results regarding what the drivers of variability experienced for different data.**

Keywords-wind power integration; variations; indices for variability; variable renewable energy sources

I. INTRODUCTION

The inherent variability of power generation clearly distinguishes variable renewable energy sources such as wind and solar power from other types of power generation. Characterization and comparison of output variability between different geographical locations helps to estimate the challenges of integrating significant amounts of wind generation to the stable operation of power systems. Characterizations and comparisons of output variability can also be used to demonstrate which specific characteristics cause variability [1],[2].

Reasons for variations in wind power generation of an individual wind power turbine are manifold and differ between different time resolutions. From second to second, generation is generally quite stable due to inertia of the rotor. From one minute to several minutes, larger ramp rates can occur because of wind gusts passing thru the plane of the rotor. Likewise changes in hourly average can be large for single wind turbines. [3]

When several wind power plants are aggregated in one power system, the characteristics change significantly and are generally smoothed [4], especially on hourly and sub-hourly time scales. For the operation of the power system, this implies, for example, a reduction of per unit balancing needs. However, this holds only as long as transmission between the different areas of wind power generation is available; otherwise, variations within the same time horizon cannot balance each other. Because variations rarely, if ever, exactly offset each other, balancing - with other power plants or with demand side measures - is needed to keep the system stable [5].

Wind power variability increases the variability of net load – that portion of demand that must be balanced by conventional power plants and demand response. To understand and optimise for variability, a variability index is proposed. The index enables us to examine the impact of country-specific details in a compact and straightforward manner. This makes it possible to compare different power systems from the perspective of variability, like how geographical characteristics and weather conditions impact wind power generation. Calculating variability indices takes much less effort than running full scale wind power integration studies. Therefore, variability indices can be used as a fast first estimate of balancing challenges when comparing a less-analysed system to a more-analysed system with a similar variability index. In addition, a suitably-defined variability index can be compared with an estimate about the flexibility available in a given power system.

Variability can be assessed as a change between two discrete points in time. Alternative approaches use power spectral densities, wavelet transforms or conditional range metrics. The first approach is, for example in [6], applied to quantify wind power variability as a function of installed wind generation capacity. The second approach is utilized in [7] to present characteristics of wind power and load variability. The latter approach is used in [8] to quantify the impact of turbine size and generator characteristics on variability.

In literature, variability indices sometimes also refer to indices used to detect fast changes in power generation (fluctuations) in order to optimise forecasting systems, e.g. [Davy2010] or [9]. However, our objective is to identify an index to compare different power systems.

II. Variability Index Method

The proposed variability index is an index with two dimensions. These dimensions are the ramp duration (e.g. one hour) and the exceedence level of the ramp (the level that x % of the ramps do not exceed). Since ramps take place both upward and downward, both directions are considered. The index can be weighted, if some of the components are estimated to be either more important or represent a larger quantity of ramps than other components.

The exceedence value for each index term is calculated from absolute ramps in order to allow both up and down ramps to increase the index value (eq.1), where *exc* is the ramp at the exceedance level, *t* is the ramp duration, and *i* is the exceedence level, and *w* is weight given to specific ramp duration / exceedance level. The analysis is performed for capacity factor time series (generation level MW per rated capacity MW) and therefore the index has some physical correspondence – it is a ramp corresponding to the weighted average of the component ramps (different duration and exceedance level ramps chosen for the index).

$$\frac{\sum_{t,i} w_{t,i} \times | \, exc_{t,i} \, |}{\sum_{t,i} w_{t,i}} \qquad (1)$$

Exceedance levels are often chosen as multiples of the standard deviation σ. This can create confusion when upward and downward ramps are distinguished. In this paper e.g. upward 4σ is calculated so that 99.996833 % of ramps are below the 4σ upward ramp – including all downward ramps. Similarly 99.996833 % of ramps are above the downward 4σ ramp level – including all upward ramps. Therefore, 99.993666 % of all ramps fall between the 4σ downward and 4σ upward ramps.

III. Cases

TABLE I. Cases in the paper

	Years	Wind share	Dispersion within area	Area size
Finland FIN	2005-2012	0.19-0.57 %	Dispersed, but number of sites limited (<40)	300 x 800 km
Norway	2007-2013	0.7-1.5 %	From concentrated to dispersed, number of sites limited (<30)	300 x 1700 km
Sweden	2007-2013	0.95-7.48 %	Well dispersed	
Denmark west DK1	2009-2011		Well dispersed	
Denmark east DK2	2009-2011		Well dispersed	
Bonneville Power Admin. BPA	2007-2014	4.2-18.8 %	Mostly concentrated	200 x 200 km

Table I lists the data available for the analyses – the data are real historical wind power production time series from large scale wind power production – so aggregated wind power data from several wind power plants in a larger area.

IV. Factors Influencing the Index

The relation between the size and the length of the ramp in the wind power generation can be seen in Figure 1. The circles in the figure indicate different time spans of interest in the power system operations. Lower left circle presents intra-hour operations, where variability influences the need for balancing (load following or secondary/tertiary frequency control reserves). In some systems this period should be shorter, e.g. 10 minutes, but many systems do not have data available at that resolution and therefore one hour is used in this paper. Primary reserves are not directly influenced by wind power and tertiary reserves are mainly due to wind forecast errors – not variability. The middle circle indicates region where wind power induces most ramping needs and may cause additional start-ups of thermal plants. Power plants with less costly start-ups can shut-down or start-up for shorter time spans than power plants with more costly start-ups and they can be impacted in this time scale. The third circle is in the region where variability influences the power plants with more costly start-ups and has increasing influence on the use of storages, e.g. hydro power with daily reservoir. This is naturally a gross simplification of the impact of variability on power system operations, but it is necessary if an index is to be formed.

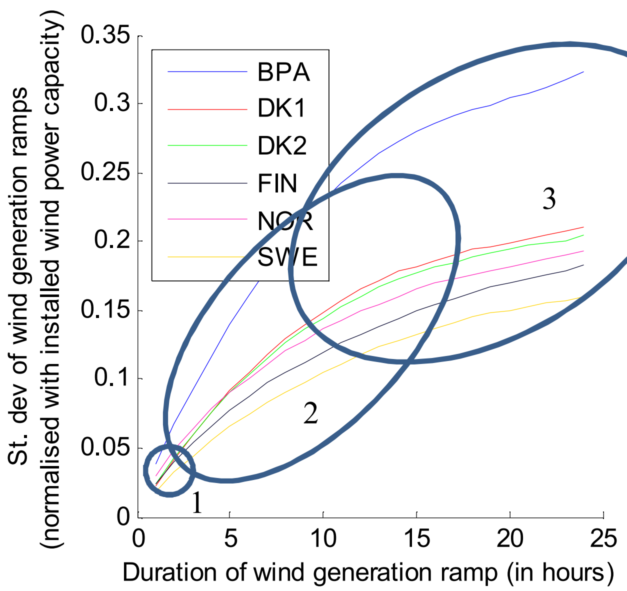

Figure 1. St. dev. of wind power generation deltas

The exceedence level shows the size of wind power generation ramps that exceed a selected share of all ramps. The data includes both upward and downward ramp exceedence levels and the exceedence level therefore starts from 50 % in Figure 2. The first segment presents most of the ramps and has therefore the highest economic impact. The second segment includes ramps that may cause notably higher costs per ramp. The third segment consists of the highest ramps, which cause a need for additional reserves whenever they are difficult to predict, which they may often be.

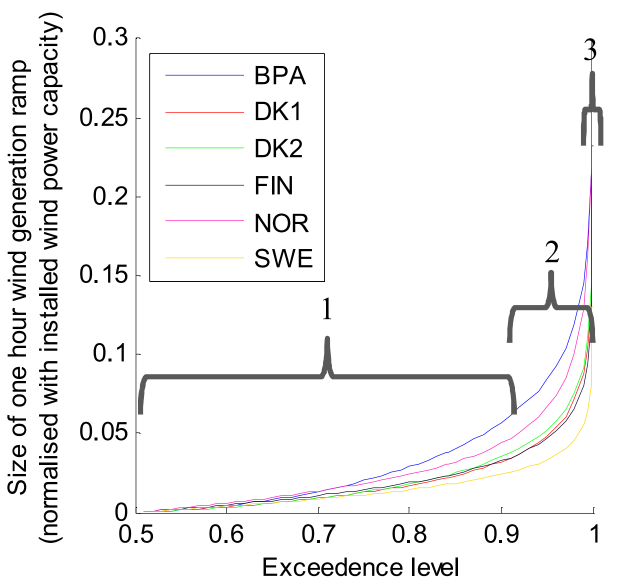

Figure 2. One hour ramps in wind power generation at different exceedence levels.

It is of course arbitrary to divide the wind generation ramps into the categories above. However, this was done for the purpose of getting one value that would reasonably present the variability in a given power system considering these two dimensions. A more correct approach would be to try to estimate the economic impact of different ramps in a given system, but this would be a difficult undertaking. More importantly this would not likely be worth the effort, since the variability index is not meant for accurate economic analysis – it is meant to give a first order approximation of the variability in wind power in a given system and to enable rough comparisons between systems.

Sensitivity of the index

In order to test how sensitive the variability index is with respect to the set of ramp durations, the exceedence levels and their weights, the variability index was calculated for several different set of values. We started the analysis by using a weighted variability index and therefore the sensitivity analysis involve a number of perturbations from the set #1 'Weighted', which can be seen in TABLE II. Vertical values in the weight column refer to ramp duration and horizontal values refer to exceedence levels. For example, the combination of 4 hour ramp duration and exceedence level at 1σ has a weight of 4 in set #1. The upward and downward exceedence levels could in principle have different weights, but this was not considered and therefore the weights in TABLE II. apply both to downward and upward ramps in same manner.

TABLE II. ASSUMPTIONS FOR VARIABILITY INDEX SENSITIVITY SETS

Set name	Ramp durations	Exceedence levels	Weight
Weighted (set #1)	1, 4, 12	1σ, 96 %, 4σ	2 4 2 1 2 1 1 2 1
Uniform weights (set #2)	1, 4, 12	1σ, 96 %, 4σ	All 1
Modified weights (set #3)	1, 4, 12	1σ, 96 %, 4σ	2 1 2 2 1 2 2 1 2
12 hour ramps (set #4)	1, 2,…,12	1σ, 96 %, 4σ	All 1
24 hour ramps (set #5)	1, 2,…,24	1σ, 96 %, 4σ	All 1
All exceedence levels (set #6)	1,4,12	All	All 1
Longer ramp durations (set #7)	1, 6, 18	1σ, 96 %, 4σ	2 4 2 1 2 1 1 2 1
Two-by-two (set #8)	1, 12	1σ, 3σ	All 1

Figure 3. displays the resulting variability index with different sensitivity sets on the x-axis. There is naturally variation in the index, since some of the sets include quite different duration of ramps or exceedence levels. For example set #6 includes all exceedence levels that have been calculated. The exceedence levels cover the whole range with one percent steps (50 %, 51 %, 52 %,…) plus sigma levels (σ, 2 σ, 3 σ, 4 σ). The ramp in most exceedence levels is small and therefore the resulting variability index is much smaller than in other sets, where only selected exceedence levels have been used with the assumption that the large ramps are more important than small ramps to power system operation.

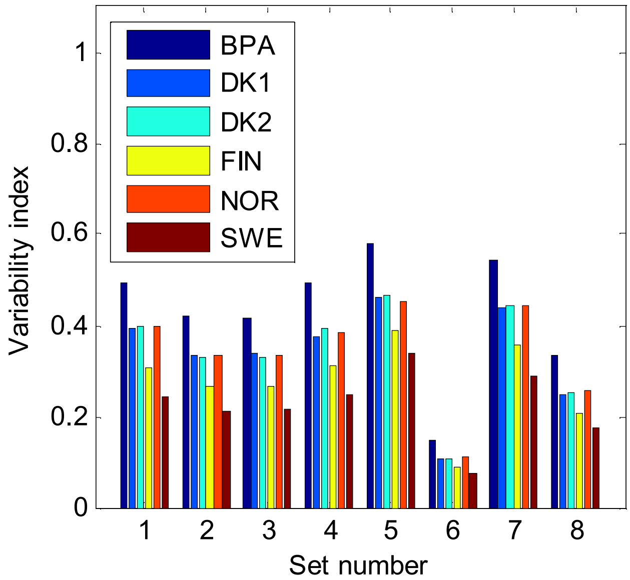

Figure 3. Variability index calculated with different sets of ramp durations, exceedence levels and their weights

What is interesting is not really the absolute level of variability index and how it changes. It's more important to see how the variability index changes relatively. Hence, Figure 4. shows the variability indices of other countries in relation to the Finnish one. The figure demonstrates that for most sets the changes are very small. However, when including all ramp durations (set #5) or all exceedence levels (set #6), the index starts to have some relative differences between countries. However, these sets are considered to be poor from the point of power system operations and hence only demonstrate how robust the relative index is to the choice of different sets. Set #7 is interesting, since it takes ramp lengths of 1, 6, and 18 hour ramps instead of the 'Weighted' 1, 4, and 12 hour ramps. It seems like the index has some sensitivity to this choice – and the choice is arbitrary at this point. Set #8 shows that it might be enough to use a smaller number of categories.

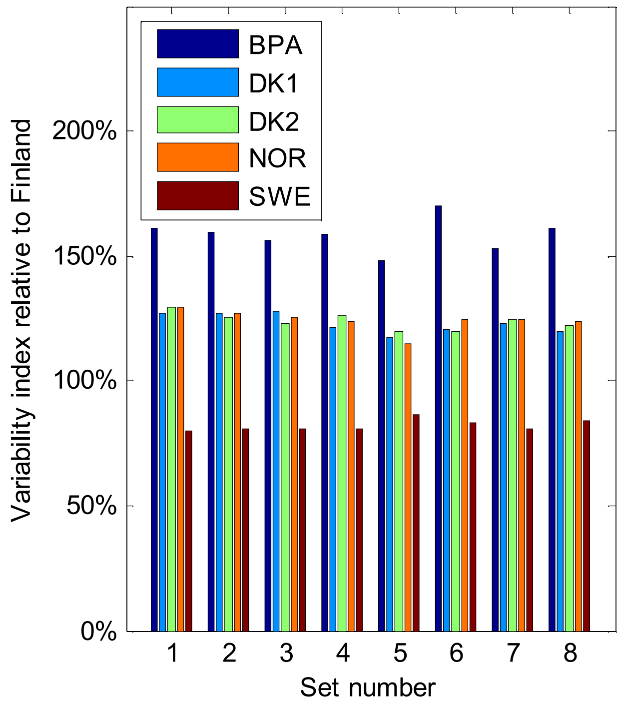

Figure 4. Variability index in relation to Finland for different sets of ramp durations, exceedence levels and their weights

The data from each country contain multiple years, which each have different variability due to changes in wind turbine fleet and its dispersion as well as windiness of the year among other things. Hence, Figure 5. shows the variability index in Finland for different sets relative to year 2005. Each set shows very similar variability indices for the analysed years.

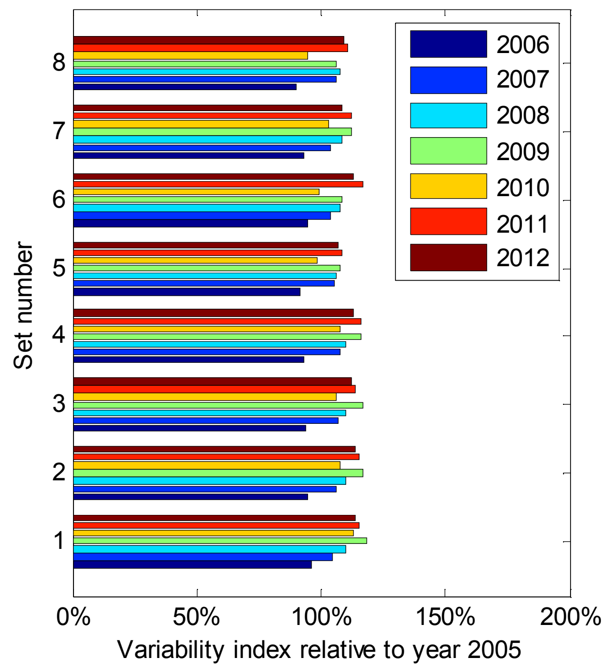

Figure 5. Variability index in Finland in relation to year 2005 for different sets of ramp durations, exceedence leves and their weights

V. PROPOSAL FOR VARIABILITY INDEX

Based on the sensitivity analysis above, there was no big difference between different meaningful sets. Hence, it was decided to recommend the utilization of uniform weights using the set #2 as long as there is no better analysis to back up using weights. A more important decision would be to select which ramp durations to include. We have somewhat arbitrarily chosen 1 hour, 4 hour and 12 hour ramp durations. An economic analysis comparing the impact of variability in different time scales could improve this choice.

VI. CONCLUSIONS

The article presents a method to generate an index for wind power variability – i.e. the ramps in wind power generation. Variability was considered to contain two dimensions: duration of the ramp and the exceedence level of the ramp. The index was formed by taking the average from absolute upward and downward ramps of different ramp durations at different exceedence levels. It was shown that the index will change considerably depending on which ramp durations and exceedence levels are chosen. However, the index composition could change quite a lot and it would cause only small changes in the relative index between countries. Finally, a proposal was made for index composition. Future work could use this index, or variations on this formulation of the index, to compare variability of wind energy, demand, solar energy, and net load.

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