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Impact of Wind Generation Fluctuations in the Design and Operation of Power Systems

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Abstract-- In this paper, the impact of the wind time variability and the spatial smoothing effect in mountainous complex terrains, usually taken as 1/sqrt(N) for fast fluctuations, is studied. The dimension of the regions, the type of electrical clustering of large numbers of wind turbines and the local meteorological effects are addressed and conclusions drawn on selected experimental case studies.

***Index Terms*—Dispatching, Power generation scheduling, Power system control, Wind power generation,**

I. INTRODUCTION

THE fluctuations of the power delivered by a wind power plant are a trademark of this form of renewable energy [1]. While this may be a concern in what concerns the fulfillment of power quality standards (e.g. IEC 61400-21 [2]), the fast fluctuations are mostly uncorrelated and tend not to be noticed by the Transmission System Operators (TSOs). However, with the increasing penetration of wind power in certain European countries and control areas, it becomes of major pertinence to characterize the slower (minutes to hours) fluctuations, both in the time and in frequency domain, as well as the driving forces behind the so-called "fluctuation's smoothing effect".

In fact, even if the very fast power fluctuations in an whole region are mostly uncorrelated and cancel themselves, there is little knowledge about the reason why, for instances, countries as Portugal or the US experience slightly higher wind power fluctuation values than the measured in most Nordic countries. These local/regional fluctuations may apparently not affect the TSOs, but may also introduce hazardous oscillations in parts of the grid (or even intra-system oscillations), and therefore need to be carefully assessed, especially since very simple aggregation methods assuming no wind correlation effects are already being used in by some TSO planners.

II. THE IMPACT OF THE WIND GENERATION FLUCTUATIONS IN POWER SYSTEMS

A. *The state of the art of wind power fluctuations assessment*

Nowadays, when wind power is mentioned in the innumerous fora that take place every year, the common sentence that comes out of every discussion, even by persons with no technical background in power systems is "grid integration". The grid integration terminology has been used so widely and with so many senses that nobody knows anymore what exactly people mean by that. In the old days of the early nineties of last century, when these subjects started to be studied and addressed, grid integration (of wind generation) usually meant the impact on the local grid where a specific wind park was to be installed. So the major points to address then were the voltage variation, the reactive power consumption by the wind park and, in overall terms, the power quality issues. Those initial concerns on "grid integration" of wind power gave room to the development of the first standard for wind power quality IEC 61400-21 published in 2001. In it, the fluctuations of wind generation were first addressed and later quantified by weighted parameters as flicker and voltage dips, both under stationary and transient operation of the wind park.

It was clear since the beginning of the IEC standard works to characterize the wind power quality, that it was necessary to characterize the effect that the aggregation of wind turbines had on those parameters, namely to develop mathematical or statistical expressions to infer the behavior of the wind park based on the data provided by the power quality tests performed to a single wind turbine, according to the specification of methodologies prescribed by IEC 61400-21.

At those days, the pressure was enormous in order to produce a standard that could prove wind turbines didn't harm the overall quality of the grid and to define methodologies that enabled to separate the waters between the manufacturers that produced "good power quality" wind turbines, from the others that delivered equipments characterized by hazardous output power (and consequently, voltage) oscillations at their terminals that sometimes even affected the

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protections at the nearby substations. Therefore, being then a minor problem, the effects of the wind turbine's aggregation on the output fluctuations was taken in a rather light manner, using the expression theoretically derived by N. Lipman [3] in the 80's for the ideal behavior of a cluster of infinite wind turbines driven by totally uncorrelated wind time series. This so-called *smoothing effect* of the fast fluctuations for an ensemble of wind turbines is more notorious for large number of wind turbines sharing a common electrical connection, since that situation embodies the ideal condition of Lipman's approach that enable to define the smoothing effect as:

$$\sigma\ (P_{WP}) = \sigma(P_{WT})/sqrt(N) \qquad (1)$$

where $\sigma(P_{WP})$ represents the standard deviation of the output's power ensemble and $\sigma(P_{WT})$ the standard deviation of an individual wind turbine. The proportional factor, *sqrt(N)* is the squared root of the wind turbine's number (*N*). Lipman's work, later also confirm in the frequency domain by Beyer [4, 5] when he addressed and defined the *1/sqrt(N)* cancellation rule for the fast fluctuations was (and still is) a reference in this area, and moreover has been extremely helpful when no wide experimental data from wind parks and wind turbines was available to perform statistically representative tests.

Nowadays, although many non-experts still refer to this area as the "grid integration challenge", the focus of researchers and scientists is first, on the stable and manageable operation of power systems with large amounts of wind generation, and second, on the design of the future power systems, that will have to cope with wind penetrations in the order of two digits, specially with the recent European directives, focusing on a 20% renewable penetration in 2020.

Although the characterization of the wind turbine's power quality is still a major issue, especially since that is a guarantee of the non occurrence of disturbances on a local grid level, the TSOs are concerned, and very reasonably one may state, about the fast growth rate of the wind generation penetration in power systems. That concern lead to the development of "grid codes" where wind parks were elevated to the adult category of "power plants" and thus asked to fulfill several power system requirements as voltage control, power ramps limitations, sometimes even contribute for the system's frequency control (by deloading of wind turbines), but mostly, they defined the minimum response of wind turbines to transient events, mainly short-circuits and/or losses of conventional generation. The advent of grid codes, although contested by many wind turbine's manufacturers is to be cheered, since it allowed to climb another, and possibly one of the most relevant steps, for the wind technology: most wind turbines are nowadays able to respond as requested by the TSO's and defined in theirs (huge number!) of codes, and that enabled the entering of the sector in the "wind power plant" era.

Grid codes are in interesting theme and one extremely relevant for the wind sector, but they do not address - unlike the power quality standard IEC 61400-21 - the variability of wind power generation, and therefore are out of this scope of this paper.

B. *The relevance of wind power fluctuations*

The fast fluctuations of the power delivered by a wind power plant are mostly uncorrelated and tend not to be noticed by the Transmission System Operators (TSOs). However, slower fluctuations, depending on each region's wind climate, do not always show the same useful behavior. The increasing growth rate of wind capacity in certain areas of European obliges to characterize these fluctuations, something several R&D projects and teams started to do recently.

The graphic depicted at Fig. 1, developed under IEA Wind Task 25 [6, 7] gives a clear view of what may be the time and space scales of the relevant fluctuations, i.e, the characteristic variability with a higher impact on the operation of power system and therefore, on its design.

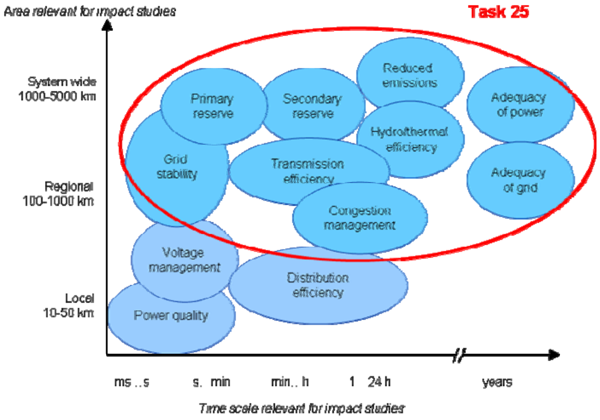

Fig. 1. Time scales and dimension of areas relevant for the design and operation of power systems [6].

The wind generation variability, according to IEA.Wind Task 25 previous graphic, is especially relevant in a range that goes from seconds (voltage and frequency regulation) till several hours (unit commitment), passing by the "below minute till some minutes" characteristic oscillations of primary reserve.

Having in mind that each country or control area, depending on its energy mix structure, has its unique problems and capabilities of integrating wind power, one should consider, however, that the basic characteristic – the wind generation fluctuations - are independent of the power system under study, since they are autonomously driven by the atmospheric flow characteristic oscillations. Moreover, they are also impossible to solve or reduce through effective wind production forecasting systems – a tool required by every country or control area nowadays – since, unfortunately, we can forecast the wind variability within a certain confidence interval and minimize its impacts on the power system operation, but we cannot change it or reduce the amplitude of its fluctuations.

For the above reasons, the variability of the wind generation – many times incorrectly referred as *intermittency*, although fortunately this term is losing acceptance - specially when statistically characterized, may be extremely relevant in the design of power systems and, specially, in the acceptance (or not) of added wind capacity in certain areas of the network.

Taking, as an example, the spatial strong smoothing effect, evident even for the very slow fluctuations illustrated by the IEA Wind Task 25 state of the art report [6], leads to clear directions in what concerns some tendency of conservative system planners to attribute to the whole wind capacity, the characteristics experimentally obtained for individual wind parks.

III. CHARACTERIZING THE WIND POWER VARIABILITY

A. *Wind Flow and Wind Power Fluctuations*

Although many authors have been referring to the wind power variability (or intermittency) for decades, few recent systematic approaches exist to characterize its behavior.

On the other hand, the fluctuations of the atmospheric flow are quite well known, being the *wind spectrum* of Fig. 2 the most common representation of its energy content over the meteorological synoptic range.

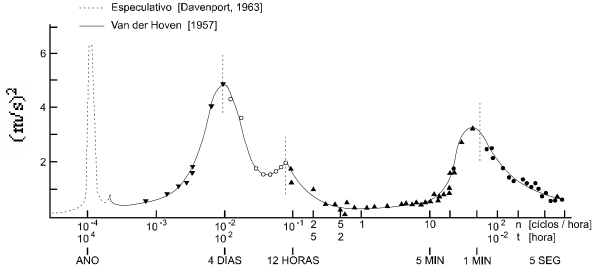

Fig. 2. The van der Hoven wind spectrum was measured by the author in the fifties at the Broohaven National Laboratory and is still used as reference for wind engineering worldwide. It is also used in several national codes for the wind actions on structures. [8].

The reason for that situation lays partially in the fact that although the wind resource measurements sites are spread on a country's or even continents scale, usually with simultaneous (hopefully synchronized!) recording systems, that information is not directly and easily transferred to the wind power for several reasons. First, wind turbines are equipments with a non-linear behavior, i.e. P=f(v) is a non-linear, many times non bijective function. Second, the wind doesn't have Gaussian distribution, showing a strong asymmetry with respect to its mean, being its fluctuations normally represented by a Weibull distribution function. Third, the fact that the atmospheric flow is a tri-dimensional, non-stationary and non-ergodic meteorological variable also doesn't contribute to a straightforward approach [8, 9]. All of the stated above adds to the fact that the grid to which a wind turbine or wind park is embedded has also an impact (usually through the short circuit power on the point of common coupling and the interconnection transformers) on the phase and amplitude of fluctuations generated by that power unit. The described situation has prevented most of the existing authors from obtaining the typical characteristics of the fluctuations generated by wind power plants.

Only recently, with the pressing impressive growing rate of the wind power capacity, but also due to the implementation of wind forecasting and monitoring tools (e.g. IEC 61400-25, [10]) lead to the beginning of several wide experimental campaigns conducted by National Laboratories, TSOs and electrical utilities with large wind penetration. Those valuable initiatives and the access given by some institutions to the data collected enabled several scientists to recently address this issue in a systematic form for the first time [6, 10, 11]. From all these campaigns, it is of special reference the comprehensive data under collection in the United States by the National Renewable Energy Laboratory - NREL, especially by the fast sampling frequencies under use there, usually of 1 Hz, in some special circumstances, higher [11]. In Europe, most data already collected shows simultaneously information from single wind turbines and the whole wind parks generation and it is being recorded mainly due to recent TSO requirements related to the forecast procedures and methodologies, and thus it has sampling periods in the order of 10, or even more frequently, 15 minutes.

B. *Wind Generation: a new Fluctuating Plant in the Power System*

Power system planning dealing with grid and power units adequacy, usually has time periods of several years, sometimes decades (see Fig. 1), what may raise some questions about the existence of a close relation among that activity, and the occurrence of wind power fluctuations, that are a phenomena characterized by a typical period raging from below some minutes (fast mechanical turbulence driven fluctuations) and some days (wind climate driven oscillations)

That relevance appears evident from the easy operation of some power systems with large amounts of embedded wind generation, when compared to some other power unit structures. That technical easiness also reflects the so-called integration costs, these later on the financial side. Power systems exist where the added costs by integrating wind are so low, that can be considered negligible, while others show considerable higher values.

The key for an easy "grid integration" of the wind power is a structure of the power system where the response to very fast (virtually unpredictable) fluctuations is technically easy and automatic, thus not requiring relevant additional costs. As an example, systems with a high percentage of hydro capacity in the mix, especially when that capacity also has embedded storage, have already proved to be the ideal power stations to provide the required adaptability to the wide range of wind fluctuations and thus contribute to a manageable and “easy to operate” power system.

Nevertheless, even when countries or control areas are in the comfortable situation of compensating the large wind power fluctuations with “easy to regulate” hydro power plants with storage – that for many power engineers emulate the “ideal power station” – it is necessary and required to know the characteristics of those fluctuations in order to provide those fast-responsive plants with the automatic remote systems for voltage and frequency control that are more adapted for the needs of each power unit portfolio. Moreover, in what consists the strategic operation of the power system, namely the hierarchy of the dispatch in terms of unit commitment cannot ignore the fluctuating non-controllable characteristics of the wind power, when this source of energy starts to provide an annual percentage of consumption above 10%, as it is already the case of Denmark, Spain, Portugal and some regions of Germany.

It is a known reality that in isolated islands with large wind penetration, the old manual controlled diesel power units operated much better than the new automatic units that tended to regulate in a rigid form and compensate “all” the (fast frequency) wind power variations. In the latest situation, it was not uncommon some years ago to end up with several voltage (and even frequency) controllers destroyed after some weeks, especially when the systems were very rigid, i.e. had very tied limits for the frequency variations.

It is clear and obvious that the large interconnected systems with the thousands of power stations have nothing to do with small isolated islands. However, there is a lesson to be learned by the fact that the latest, more advanced and fast control system and regulator are nor always the ones more adapted to wind power – sometimes ignoring those variations when within the stable limits defined by the power quality standards and grid codes may give better (and less expensive) results.

IV. THE WIND GENERATION DEVIATIONS IN PORTUGAL

A. *Taking wind variability into account*

The term fluctuations is widely used in the literature when referring to variations above and below the mean values, as defined in (2):

$$U(t) = u_{av} + u \qquad (2)$$

where $U(t)$ is a quantity variable in time, u_{av} represents its average value and u represents the fluctuation with respect to the average value.

Although statistically, the definition of (2) is the usual one for describing the fluctuating component of one time depend variable, that definition is not the most useful to describe the wind generation variability with respect to the power system operation, since the concern here lies on the perturbation of existing operating conditions of the instant “*t*”. Therefore, one may define to characterize the wind power (relatively slow) time variations as:

$$U(t+\Delta t) = u(t) + \Delta u(t)\,/\Delta t. \qquad (3)$$

And use these “variations” rather than the common “fluctuations” defined statistically. To assess these variations in the Portuguese power system a set of data from 28 wind parks ranging from an installed capacity of 2 MW till 112 MW, totaling approximately 600 MW and geographically spread all over the country as depicted in Fig. 2 was used.

Fig. 3 - Location of the wind parks used for the current study in conjunction with the Portuguese transmission network

B. *The spatial smoothing.*

In a first approach, the spatial smoothing effect was assessed. For this, and according to the methodologies already used in the IEA Wind Task 25 [6], it was calculated the standard deviation of the power variation, as defined in (2), of different sets of wind power plants, aggregated by their spatial distribution. The results obtained are represented in Fig. 4.

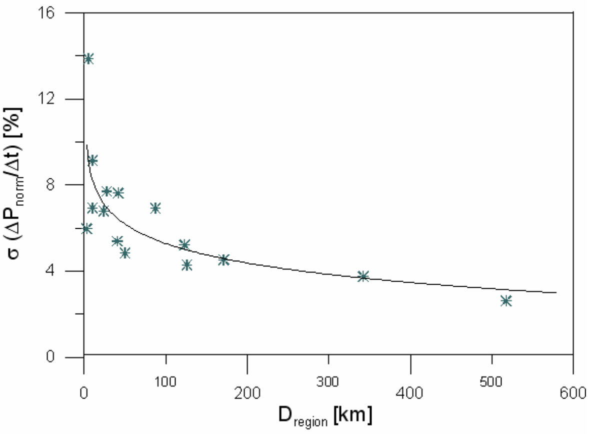

Fig. 4 – The smoothing effect of variations produced by wind power plants geographical dispersed in Portugal.

C. The turbulence effect

In the comparative studies performed under IEA Wind Task 25, it was possible to conclude that, although all regions under study show a strong and systematic cancellation effect of the spatial variations, some control areas appear to experience stronger smoothing effects than others. Taking into account the impact of the different orographies in the wind climate, especially in the turbulence, that effect was addressed and is represented in Fig. 5. It should be noted though that the (rather high) values for the turbulence do not correspond to effectively measured data, but to the output of mesoscale models for the locations of the correspondent wind parks.

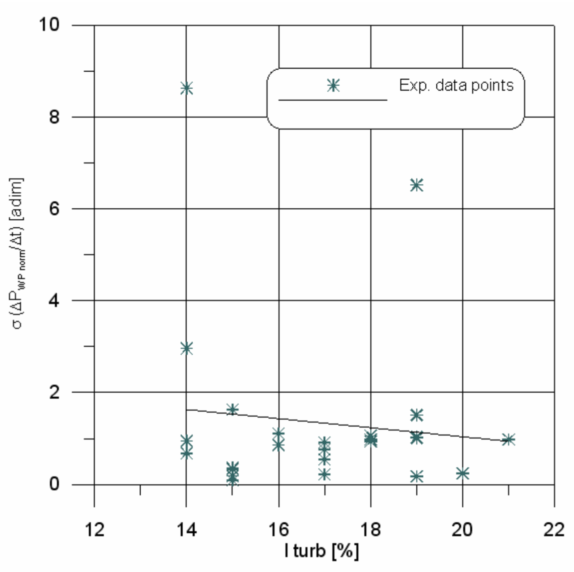

Fig. 5 – Variations of the wind parks' output power versus the simulated local turbulence.

According to the results obtained and represent in Fig. 5, and although the turbulence values were simulated rather than measured, one may conclude that this wind parameter doesn't seem to have any relevant impact on the power variations of the studied wind parks. Nevertheless, in what relates to this climatic parameter, more in depth studies based on experimentally obtained turbulences should be made.

D. The clustering effect

In order to plan the deployment of added wind capacity in areas of the grid that already have large amounts of wind generation embedded, it is very useful to assess how the power variations of the wind parks relate with the variations of the power output from individual wind turbines, namely if the "smoothing factor" 1/sqrt(N) identified by Lipman in ideal conditions for the fast fluctuations, also applies for the slow variations computed after the experimental data sampled in periods of 15 minutes represented in Fig. 6.

A simple observation of Fig. 6 enables to conclude that there is a common behavior and tendency of all wind parks studied, with the two exceptions. These exceptions were two very large power plants, both above 100 MW and equipped with the largest commercially available wind turbines (Pnominal≥2.5 MW).

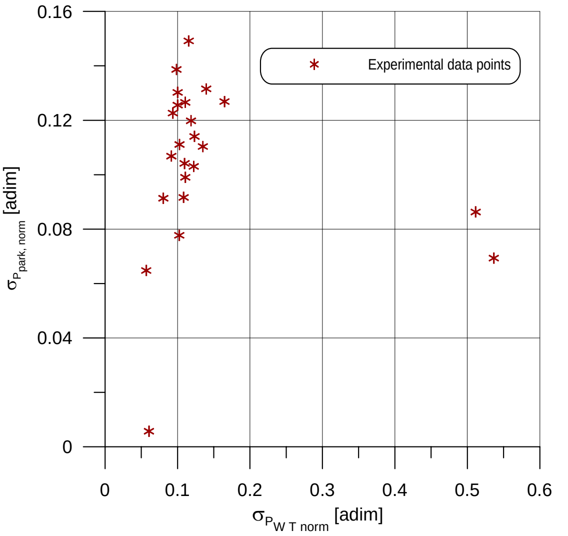

Fig. 6 – Standard deviation of the wind power plants *variations* (normalized by nominal values) against the standard deviation of the wind turbine *variations* (also normalized by nominal values).

This result, although very positive for the power system planner, raises some concern at the level of the wind park and local grid designer, specially since the large variations that occur with the wind park pose added difficulties specially in the settings of the wind park's internal protections.

The exclusion of the two atypical and larger power plants represented in Fig. 7 enabled to quantify the clustering effect of the wind parks. The bi-logarithmic relation obtained indicates a tendency of 3% ratio.

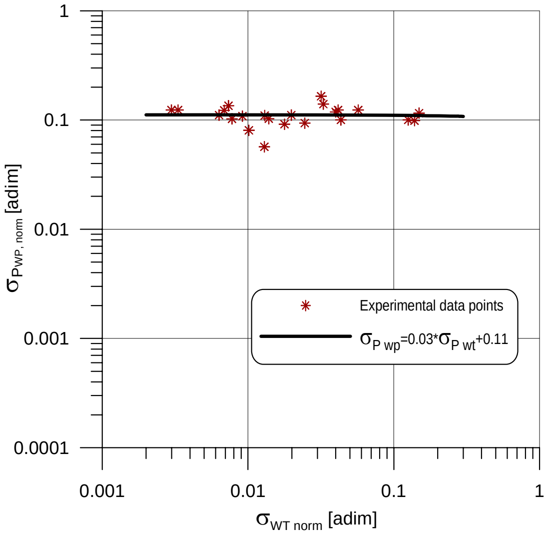

Fig. 7 – Standard deviation of the wind power plants *variations* (normalized by nominal values) against the standard deviation of the wind turbine *variations* (also normalized by nominal values), excluding the two atypical large turbine/power plants.

E. The smoothing aggregation effect

The pursue of a "smoothing ratio" in the aggregation of wind turbines in parks or regions of the grid lead to the representation of the wind park variations, (in per unit values), normalized by the number of wind turbines installed in the park (N), with respect to the variations produced by the individual turbines of each wind park, in percentage of their nominal power. The results are illustrated by Fig. 8 and they show a strong clustering effect, but also a relation with the wind park structure.

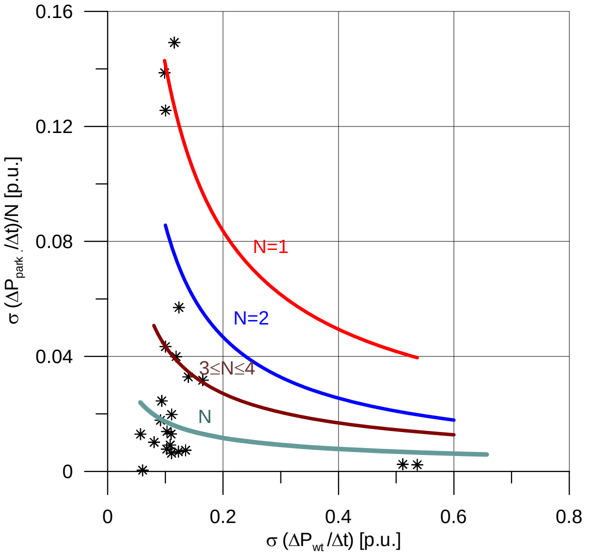

Fig. 8 – Standard deviation of the wind power plants *variations* (normalized by N) against the standard deviation of the individual wind turbine *variations.*

The upper 3 points of Fig. 8 correspond to wind parks with single wind turbines, while the two points depicted on the extreme right on the bottom of the graphic correspond to the large wind parks (above 100 MW) equipped with modern very large wind turbines.

Finally, and possibly that consisting on the more relevant result obtained with this study, it was possible to identify an define a maximum function of the wind park variations (in p.u.) with respect to the power variations of the individual wind turbines as represented in Fig. 9.

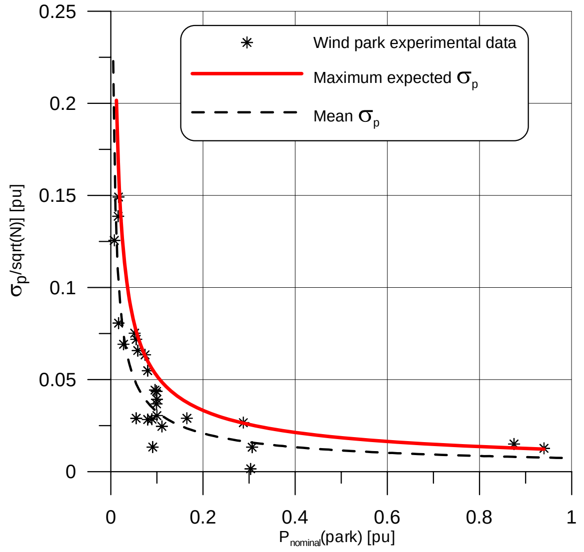

Fig. 8 – Curve of the maximum standard deviation of the wind power plants *variations* against the standard deviation of the wind turbine *variations*.

V. ANALYSIS OF THE RESULTS

The results presented in this paper correspond to a work in progress. Nevertheless, it was possible to extract several interesting conclusions from the analysis of the fluctuations and the variations of the power output of the wind power plants and wind turbines studied. The most relevant tendencies, so far, are the fact that, the spatial smoothing effect is strong and systematic on the scale of a country or control area. However, locally, the variations depicted in Fig. 4 do not always smooth out - specially below the 100 km range - and on the contrary they even seem to synchronize, whilst the factors behind that apparent reinforcement of the power variations remains to be identified.

On the other hand, the local turbulence, being a meteorological phenomenon extremely relevant in the same frequency range as the slow power fluctuations, doesn’t seem to play a relevant role in the overall variations of the wind power plants addressed in this study.

The most useful output of the study conducted, so far, lies on the identification of the maximum variation curve, with respect to the power variations injected by a wind park, with respect to the variation of wind turbine individual power, taking into consideration the 1/sqrt(N) smoothing effect identified by Lipman.

VI. SYNTHESIS AND CONCLUSION

Although the study is not yet concluded and the characterization of the fluctuations and variations of the wind generation in the frequency domain was not addressed here, it is already possible to extract some useful information.

The spatial smoothing effect on scales larger then 100 km is systematic and replicable in every power system with embedded wind generation. Whilst the amplitude of that spatial smoothing may present slightly differences from one power system to another, above a spatial scale of 500 km, the wind generation variations are below 3%.

Results also obtained recently by other authors [11] and expected by some experts in this area were obtained. These are related to fluctuations produced by very large modern wind turbines (rated power above 2.5 MW) that produce much larger power variations than their predecessors rated from 1 to 2 MW.

The aggregation effect of the wind turbines on clusters indicated to be extremely positive not only from the power system point of view, but also on the local grid operation level with a remarkable smoothing effect of the wind turbine individual variations. Finally, it was possible to identity a maximum relation between the variations of the whole wind power plant and each wind turbine, taking into account Lipman’s effect (*1/sqrt(N)*) that will enable to design wind turbine clusters and their protections in a more efficient and safe manner.

VII. ACKNOWLEDGMENT

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IX. BIOGRAPHIES

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