Statistical Study of Power Quality in Wind Farms

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1. Introduction

With this work, the intention is to complete a previous, sufficiently representative, study based on data acquisition e measurements of Power Quality disturbances in power lines connected to wind farms. The preliminary study was carried out and is described in the paper Experimental Study of Power Quality in Wind Farms [1].

The present study, as well as the previous one, was based on a power quality measurement campaign which took place in the Sotavento Experimental Wind Farm (SEWF) in Galicia, Spain, with special focus on two particular types of disturbances: Flicker and Harmonics.

The conclusions obtained from the base study suggested different approaches to the analysis of the obtained data. In order to perform an adequate data structuring, a new method of analysing the phenomena concerning Power Quality parameters was conceived. This paper describes the subsequent work performed over the data obtained at that time.

Upon data analysis using advanced statistical tools, this new study will with any luck provide the basis for the definition of a reference study method which will hopefully promote the desired data structuring, allowing straightforward application in similar cases.

2. Field Measurements in the SEWF

The data were obtained by measuring several power quality parameters and other quantities in three different locations in SEWF: in two wind turbines and in the wind farm's substation. The primary aim of the study is to obtain harmonics and flicker levels at those specific sites. Two different types of power quality measurement devices were used: UNILYZER 812 from UNIPOWER and MEMOBOX 300 smart from LEM.

The total measurement time was nearly three weeks of ten-minute measures of the main quantities chosen as relevant for the study.

One particular characteristic of the chosen wind farm lies in its technological diversity, with 5 different wind turbine technologies, as main objective of the study was to test and develop new technologies, as well as to divulge this type of energy production.

3. Data Selection

A preliminary analysis of the data obtained through the measurements taken at SEWF has revealed itself extremely hard to perform, due not only to the enormous amount of data available (which constituted a major difficulty in the selection of the data for analysis) but also in the depth of the analysis itself.

So, the need grew to take a well defined procedural path, eventually in order to build the start-point for future and more complex studies.

The data selection was performed so that only the most relevant quantities were analysed in this preliminary phase.

The data selection obeyed the following criteria:

- Filtering of data available based on empirical knowledge about the certain quantities
- Selection of quantities assuming more significant values

- Elimination of data redundancy mostly in cases were similar patterns of behaviour were observed.
- Search for significant correlations interpretable according to the theory established between available data quantities and chosen quantities.

The philosophy explained above led to the implementation of a per-phase study, as similar patterns between the three phases were clearly identified. For coherence purposes, the phase chosen for detailed analysis was the same at all sites.

For that phase the quantities chosen were: all the voltage harmonics from 0 to 42nd order, the current, active and reactive power, power factor, voltage unbalance, total harmonic distortion (THD), flicker indexes (P_{st} and P_{lt}) and wind velocity.

4. Statistical Analysis

The fundamentals concerning the following analysis were based on Time-Series Theory (TST) so that all the statistical analysis performed involved the use of specific software with good implementation of Time-Series analysis.

Basic statistics were performed, from average, minimum, maximum, median, mean square deviation to correlation matrices. Spectral analysis was performed in order to bring forward in a different way the behaviour of the time-series. Based on more careful filtering, a new selection of data was then performed.

More advanced statistical tools were used in that new selection of data. Autocorrelation analysis of the quantities was obtained, in order to study the «system's memory», *i.e.*, the degree of dependence of the present values of a given quantity on the values at previous time intervals.

Another study involved cross-correlations in order to show the dependence of the present values of a given quantity on the present and past values of other quantities. This type of analysis may eventually reveal some cause-effect relations between quantities.

The procedure was repeated for the data obtained at the three sites.

The analysis here described concerns just one of the wind turbines studied unless otherwise stated.

The main conclusions follow, divided in simple steps in order to simplify the subsequent analysis.

Spectrum analysis

A frequency spectrum of voltage harmonics in one wind turbine is shown in Figure 1.

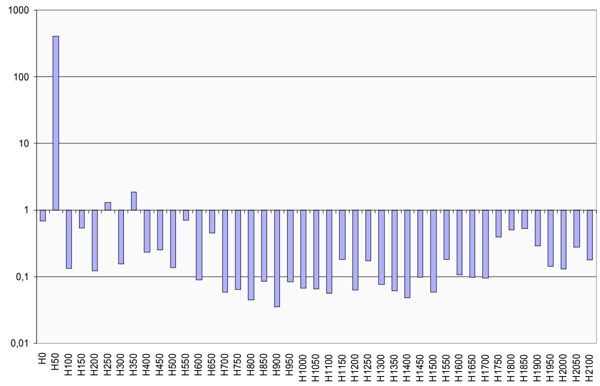

Figure 1 – Frequency spectrum in logarithmic scale for one wind turbine

The 7th harmonic shows a rather surprising prominence, followed by the 5th, 11th and 3rd harmonics.

Special mention should be made to three higher order harmonics (the 35th, 36th and 37th) which show an impressive average amplitude. In fact, these three harmonics have a relatively high amplitude (bigger than one could normally expect) when compared to their «neighbours». Another special mention should be made to the rather elevated DC component.

Autocorrelation functions

A careful look at autocorrelation functions can be crucial in examining a quantity's particular characteristics.

One first group of quantities are characterized by very smooth autocorrelation functions and very long durations of the «system's memory», which is the case of 7th harmonic, the DC component, the active power and the wind velocity.

One can say that, generally, up to 1000 Hz, the even harmonics tend to be a little more erratic and irregular and the odd ones tend to be more regular and similar to one another. This group of quantities has 30 hours of memory duration (180 ten-minute periods). Above 1000 Hz, the even and uneven harmonics tend to be more similar to each other and to have longer memory duration, up to 42 hours (252 ten-minute periods).

One close look at the autocorrelation functions of the active power and the wind velocity is in order. These two functions appear to be very similar (as one would expect) having a strong correlation to one another and with a memory duration of approximately 36 hours.

Furthermore, a reference to the almost null dependency concerning voltage wave, THD and voltage unbalance should be made.

Figures 2 and 3 depict two relevant autocorrelation functions.

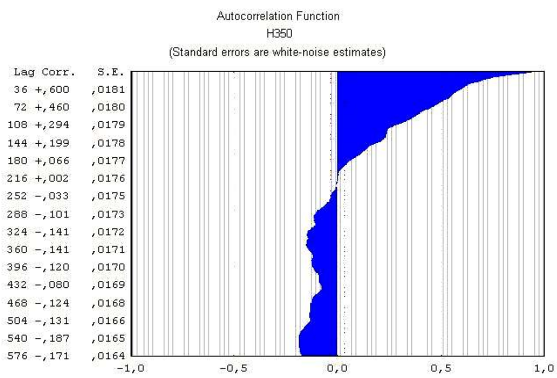

Figure 2 – Autocorrelation function of the 7th harmonic

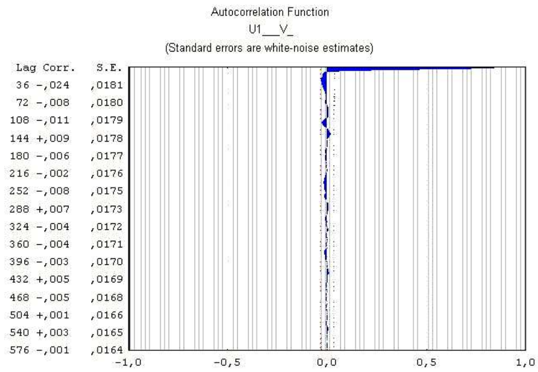

Figure 3 – Autocorrelation function of the voltage wave

Cross-correlation functions

On the other hand, a thorough study of cross-correlation functions can be of the utmost importance. There is a strong positive dependence between active power and wind velocity with harmonics 7 and 11. These functions have long memory duration, extremely strong in the first couple of hours. This type of dependence appeared rather surprisingly.

Figure 4 shows a cross-correlation function between active power and the 7th harmonic in one wind turbine.

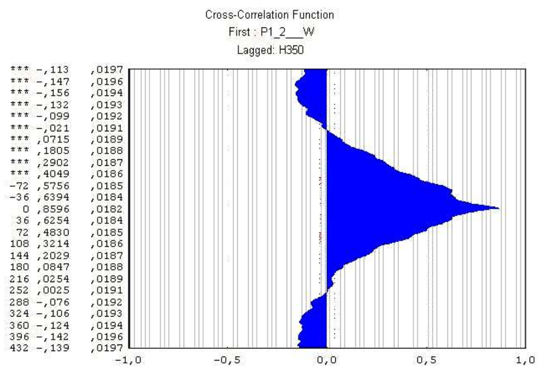

Figure 4 – Cross-correlation between active power and the 7th harmonic

Linear Regression of quantities

An attempt at modelling the relations among quantities, through linear regression, at the wind turbines and the substation was performed in order to study harmonic propagation. The quantities chosen for this particular analysis were: voltage wave, DC component, harmonics 3rd, 5th, 7th, 11th, 35th, 36th and 37th order, THD and P_{st} and P_{lt}. The average values of these quantities were considered.

With this new analysis, one can see how just these two wind turbines are a faithful representation of the whole wind park as reflected on the voltage values at the substation, including the influence of harmonics and events occurred, as witness their highly adjusted correlation coefficients. Studies were conducted so as to operate a linear regression using the values of a given quantity at the two wind turbines and «define» the value of that same quantity at the substation.

Such a procedure led to some very interesting results, partially presented in figures 5 and 6. In fact, some of the quantities at the two wind turbines influence decisively the output value of the corresponding quantity.

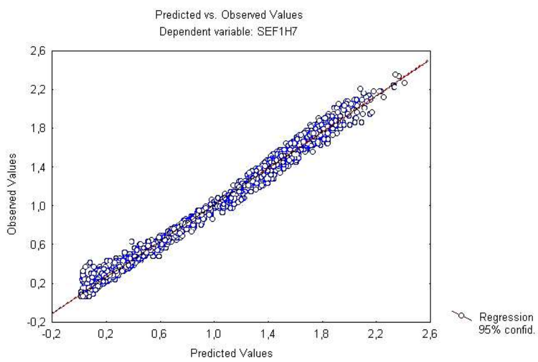

Figure 5 – Result of linear regression of the 7th harmonic at the substation in the corresponding values from the two wind turbines

Regression Equation:
0.059656xG1 + 0.015778xG2

Extremely curious results were observed regarding the voltage wave, 7th harmonic and, in a more diffuse way, in the 3rd, 5th and 11th harmonic, indicating that it is possible to predict the output value of certain quantities based only on the information from two wind turbines. Plots were made to express, for some quantities, the measured values of those quantities at the substation as a function of the values predicted by the linear regression on the corresponding quantities' values at the two wind turbines.

However, for some quantities, such as the flicker P_{st}, these relations do not apply, suggesting a much more complex structure of the voltage wave.

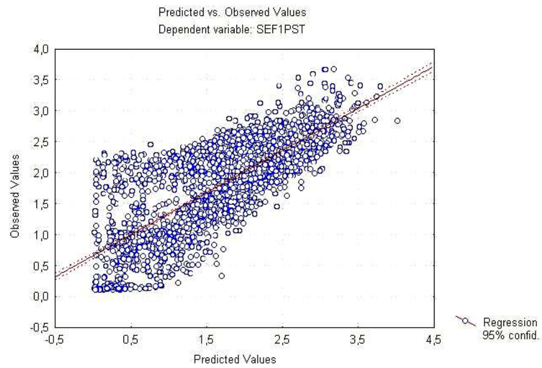

Figure 6 – Result of linear regression of the flicker P_{st} at the substation in the corresponding values from the two wind turbines

Regression Equation:
0.330201xG1 + 1.034010xG2

The main conclusion to draw from this analysis is that the study of two wind turbines from the SEWF already provides sufficient information, significant enough to allow a reasonable prediction of the corresponding quantities at the substation. This is extremely interesting due to the fact that, although the wind farm is an experimental one, with different turbines of different technologies, different generation modes and potentially different power quality, they still show a significantly homogeneous behaviour.

In what concerns the attempt at observing the harmonics propagation phenomena by means of relating some quantities in the turbines and in the substation, any conclusion drawn appears to be unwise due not only to the relatively small dimension of the study performed but also to insufficient available information about the technological solutions implemented in the SEWF for the sake of industrial secrecy.

5. Conclusions and Outlook

The innovative application of time-series analysis revealed an unsuspected complexity of the structure of the voltage wave, as well as some unexpected relations between wind speed and certain harmonics, and the occurrence of higher-order harmonics.

The theory and the methods adopted proved to be effective if wisely used.

The present results point to the necessity of more thorough studies which will implicate the acquisition of more and more carefully obtained experimental data, including the measurement of other quantities, such as intra-harmonics.

6. Acknowledgement

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7. References

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