On the Assessment of Power Quality Characteristics of Grid Connected Wind Energy Conversion Systems

Paulo Carneiro †[1], Pedro Torres †[2], Rui M.G. Castro †, Ana I. Estanqueiro ‡

† IST – Instituto Superior Técnico (Technical University of Lisbon) http://www.ist.utl.pt/
CEEL – Centro de Energia Eléctrica (Electrical Energy Centre) http://enerp4.ist.utl.pt/ceel/
Av. Rovisco Pais, 1049-001 Lisboa, PORTUGAL
paulo.carneiro@edis.edp.pt, pedro.torres@ren.pt, rcastro@ist.utl.pt

‡ INETI – Instituto Nacional de Engenharia e Tecnologia Industrial,
(National Institute for Industrial and Technological Engineering) http://www.ineti.pt/
DER – Departamento de Energias Renováveis (Department of Renewable Energies)
Azinhaga dos Lameiros, 1649-038 Lisboa, PORTUGAL
ana.estanqueiro@mail.ineti.pt

Abstract: This paper presents a wind park power quality tool, developed in MATLAB™, following the specifications contained in *IEC 61400-21* standard, being the flickermeter model constructed according to *IEC 61000-4-15* standard. Wind energy dedicated procedures and methodologies, such as the concept of fictitious grid and the two different modes of operation – continuous and commutated – are then applied in accordance with *IEC 61400-21 standard*. In order to test all the functionalities and proper behaviour of the developed tool, a case-study from which power quality related data is available, was selected. Some simulation results obtained with the developed software tool are presented with the main objective of illustrating the methodologies that have been followed in its development. Furthermore, the validation of the model implemented in the WECS power quality tool is performed against the results obtained by the certified institution that was involved in the power quality tests of Samos Island, in Greece.

Key words: wind turbines, power quality, grid integration, standards.

1. Introduction

The integration of wind parks and other renewable energy conversion systems on weak distribution grids is a major issue for both the utilities planning offices and independent power plants investors, specially having in mind that the individual group/turbine capacity already surpasses 2 MW and wind parks with a capacity in the range of 150 to 200 MW exist in most European countries.

Actually, a number of wind park developers in Europe is facing resistance from the utilities to connect their independent power plants to the existing grid, specially in remote areas served by weak systems. The wind, being a spatially dispersed source of energy that may introduce benefits in the operation of a weak radial system and often has a high correlation with seasonal loads, still induces a negative reaction on the planners, mainly due to its time-dependent non-dispatchable nature.

The existence of international standards is a major contribution to assess and increase the power quality of grid connected wind turbines, especially in what concerns the assessment of the impact that different technologies may have in weak sensitive systems. The necessity to regulate the grid connection of wind turbines and its impact on the local consumers was recognized by the IEC/CEI that published a new standard – *IEC/CEI 61400-21 (2001)*: "*Measurement and assessment of power quality characteristics of grid connected wind turbines*" [1]. In this standard, the main parameters and constraints that characterise the wind power quality are identified, some specific test methodologies to apply to wind energy conversion systems (WECS) are established and the maximum flicker emission levels per wind turbine are defined.

There is a strong need to increase both the utility confidence in this form of energy and the reliability of these power plants for the investors. This situation together with the fact that the installation of new wind parks will increasingly occur in more remote places in the years to come (typically served by weaker grids) points the urging to develop new design methods and models.

Although being a totally adult and safe technology, only recently methods and standards to assess its power quality and define the parameters to assess its impact on the utility grid started to be developed and applied.

[1] On leave to EDP Distribuição, (EDP Group, Dispatch and Conducting Management – High Voltage Dispatch), http://www.edp.pt/.
[2] On leave to REN – Rede Eléctrica Nacional, (Portuguese Transmission Grid, System Operator Division, Studies and Development Department), http://www.ren.pt/.

As an example, the knowledge about wind turbines performance most engineers and designers have is provided by a manufacturer power curve. Although it is probably wrote in the turbine catalogue that the power curve was constructed after ten minutes bins (averages both on wind and power) it is not evident from that curve that the performance of this (typical) wind turbine will continuously deliver to the grid an *instantaneous* power continually fluctuating.

By *instantaneous* is understood the digitally sampled power time series, using transducers with response time lower than 100 ms and a data acquisition system with sampling frequency above 40 Hz per channel for continuous operation of the wind turbine. The continuous (or permanent) mode refers to the generator and power system normal operation, excluding cut-ins and cut-outs.

From the investors side, since the installation of a new wind park is mostly an economical subject, often the necessary technical studies that should be performed in the feasibility phase of the wind park to guarantee the quality and the non-disturbance of the existing power system, are not addressed.

The power fluctuations – directly depended on the wind structure and on the turbines technology – that characterize the typical performance of a normal wind turbine may introduce some negative impacts on the grid that may be easily avoided. The most relevant parameters to characterize in order to assess the impact of the wind power plants on the local grid may be divided in the four main areas presented in Table I.

The identification of the factors with high influence on the quality of wind power systems, together with the development, within *IEC TC88 WG10* (International Electrotechnical Commission, Technical Committee 88 – Working Group 10 – Power Quality Requirements for Grid Connected Wind Turbines), of the parameters more adapted to the wind power embedded generation specificity, to act as quality indicators (Table II), enables not only to estimate the power quality of a wind park in its feasibility phase, but also to optimise its capacity in order to avoid the degradation of the existing network quality of service.

The application of *IEC 61400-21*, together with dynamic wind park models will enable, in a near future, to assess the wind power quality in the feasibility phase of wind power plants, thus avoiding eventual negative impacts on the existing electric grid and increasing the confidence of both the utility planners and the investors.

TABLE I – Factors with relevant impact on the power quality of wind power plants.

A)	**Wind turbine technology**
	– Type of electrical generator
	– Rigid vs. flexible construction
	– Connection to the grid
	– Tower shadow effect (upwind vs. downwind)
B)	**Grid conditions at the point of common coupling**
	– Short circuit power
	– Interconnection voltage level
	– Interconnecting transformers used (e.g. LTC)
	– Earth system
	– Voltage regulation
	– Stability and coordination of the protections
C)	**Wind park topology**
	– Number and capacity of the wind turbines
	– Turbine operation under wake flow, poor sitting
	– Characteristics of the power collecting system (X/R)
	– Possible capacity effects from the cabling system
	– Wind turbine synchronization
	– Existence of extra capacitor banks
D)	**Wind flow local characteristics**
	– Turbulence intensity
	– Spectrum of the wind 3D components;
	– Correlation of the wind series the sites within the park

TABLE II – Wind turbine power quality characteristic parameters.

A) Wind turbine
– Reference power
– Maximum continuous power
– Maximum instantaneous power
– Reactive power
B) Local grid
– Flicker
– Harmonics and inter-harmonics

2. Wind Park Power Quality Tool

A. Flickermeter model

Instantaneous flicker sensation is defined in engineering in such a way that a value of 1 (one) corresponds to the perceptibility limit of 50% of the human population. The flickermeter claims to simulate the response of the "*lamp-eye-brain*" system to the measured voltage values.

Figure 1 illustrates the flickermeter block diagram as described in *IEC 61000-4-15* [2].

The block diagram presented in Figure 1 can be divided in two parts, having Blocks 2, 3 and 4 the "*lamp-eye-brain*" system response simulation function (i.e. the simulation of the physiological phenomenon) and Block 5 the goal of calculating flicker severity P_{st} coefficient (based on the obtained flicker level values), using statistical analysis.

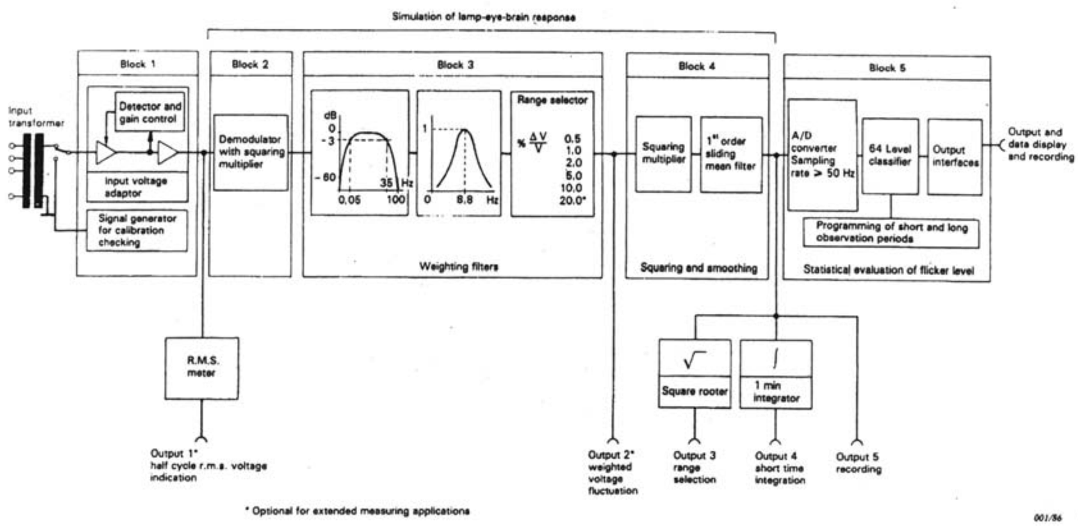

Fig. 1 – Flickermeter block diagram [2].

Block 1 converts the value of the input voltage to an internal reference level previously defined.

Block 2 consists of a demodulator that squares the referenced input voltage level (time domain). The purpose is to recover the voltage fluctuation, eliminating simultaneously the main component of the input signal (lamp behaviour).

Block 3 is composed of a cascade of filters that intend to remove the undesired frequency components (d.c. component and 100 Hz). The first filter incorporates a first order high-pass and a low-pass section, whilst the last is a band-pass that weights the voltage fluctuation according to the human visual sensitivity. In *IEC 61000-4-15* a suitable transfer function is proposed for Block 3.

The output of Block 3 is then squared (time domain) and the result will be the input of a first order low-pass filter with a specified time constant. The last two mentioned operations are to be performed by Block 4, which has the purpose of simulating the *lamp-brain* response characteristics and the storage effect in the brain (memory).

The use of Block 5 is related to methods of deriving measures of flicker severity by statistical analysis, using Block 4 output, i.e., instantaneous flicker level values. *IEC 61000-4-15* uses a defined formula to quantify flicker severity (based on an observation period of 10 minutes), P_{st}, based on the definition of some percentiles $P_{0.1}$, P_1, P_3, P_{10} and P_{50}, represent the exceeded *flicker* levels for 0.1, 1, 3, 10 and 50 % of the time during the observation period. The suffix *s* indicates that smoothed values shall be used.

It should be mentioned that this percentiles correspond to the exceeded flicker levels, i.e., its definition is the opposite of the regularly used percentile definition. Taking this into account, for a percentile P_x, one must calculate P_{100-x}.

B. International Standard IEC 61400-21

The methodology presented in *IEC 61400-21* aims at evaluating the quality of the energy delivered to the electrical grid by wind parks. This standard presents a methodology based in current and voltage measurements, taken at the terminals of a wind generator, leading to the simulation of voltage fluctuations in a fictitious grid, that doesn't have any other voltage fluctuations sources, than the tested wind generator.

In the sequence, the mentioned methodology is presented, from the fictitious grid model implementation, to the achievement of the relevant parameters, in continuous operation (flicker coefficients, $c(\Psi_k, v_a)$), as well as in switching operations (voltage change factor, $k_u(\Psi_k)$, and flicker step factor, $k_f(\Psi_k)$).

1) Fictitious grid

In Figure 2, the used fictitious grid is represented.

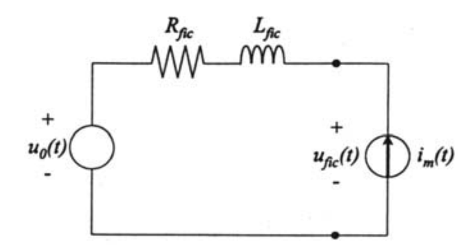

Fig. 2 – Reference fictitious grid [1].

The fictitious grid is represented by an ideal voltage source, with instantaneous value $u_0(t)$, and by an impedance formed by the series of a resistance, R_{fic}, with an inductance, L_{fic}. The wind generator is represented by a current source, $i_m(t)$, whose instantaneous value matches with the measured current value, of the studied phase. In this way, the voltage at the wind generator terminals, $u_{fic}(t)$, can be evaluated, taking into account the ideal voltage source, $u_0(t)$ and the electrical angle of the fundamental of the measured voltage, $\alpha_m(t)$.

Using complex notation, one can conclude that:

$$R_{fic} + jX_{fic} = \frac{U_n^2}{S_{k,fic}}\left(\cos(\psi_k) + j\sin(\psi_k)\right) \quad (1)$$

where U_n is the rms value of the nominal voltage of the grid and $S_{k,fic}$ and Ψ_k represent, respectively, the short circuit power and angle of the fictitious grid.

2) Continuous operation

At continuous operation, the parameter that allows estimating the quality of the energy delivered to the grid by a wind generator, in terms of voltage fluctuations, is the flicker coefficient, $c(\Psi_k, v_a)$.

For each grid impedance phase angle (Ψ_k = 30º, 50º, 70º, 85º) and for each wind speed distribution (wind mean speed = v_a = 6, 7.5, 8.5, 10 m/s), the following procedure should be repeated:

1. The measured values series (3-phase instantaneous current and voltage at the terminals of the wind generator and wind speed) allow to obtain the time series of $u_{fic}(t)$; this measures are processed in order to determine the flicker coefficient as a function of the grid impedance associated angle and the wind speed distribution.

2. The $u_{fic}(t)$ time series form the flicker algorithm (flickermeter) input, whose development was based in the *IEC 61000-4-15*, and already presented. The output of the mentioned algorithm is a flicker emission value, $P_{st,fic}$.

3. The flicker coefficient, taking into account only the dependence to the fictitious grid impedance angle, is given by (2), where S_n is the apparent power of the wind turbine.

$$c(\psi_k) = P_{st,fic}(\psi_k)\frac{S_{k,fic}}{S_n} \quad (2)$$

4. The frequency of occurrence of wind speeds, $f_{y,i}$, is described by a Rayleigh distribution; the relative frequency of occurrence, $f_{m,i}$, is then calculated, for each wind bin. This enables the computation of the weighting factor, for each wind speed bin (each bin comprehends 1 m/s), between the cut-in speed, v_{cut-in}, and 15 m/s, through $w_i = f_{y,i}/f_{m,i}$.

5. The weighted accumulated distribution of the measured flicker coefficient is given by (3), where $N_{m,i,c<x}$ represents the number of flicker coefficients smaller or equal than *x*, for class *i*, and N_{bin} is the total number of classes.

$$\Pr(c < x) = \frac{\sum_{i=1}^{N_{bin}}\left(w_i N_{m,i,c<x}\right)}{\sum_{i=1}^{N_{bin}}\left(w_i N_{m,i}\right)} \quad (3)$$

6. The flicker coefficient is the 99th percentile of the weighted accumulated distribution.

3) Switching operations

For switching operations the parameters that allow estimating the quality of the energy delivered by wind generators, in terms of voltage dips, are the voltage change factor, $k_u(\Psi_k)$ and the flicker step factor, $k_f(\Psi_k)$. Therefore, the following procedure has been implemented.

1. Equal to the case of continuous operation, with the single difference that the 3-phase instantaneous measured current and voltage, at the terminals of the wind generator, should range a sufficiently long time period, T_p, like for instance 60 s, in order to assure the disappearing of the switching operation transient state.

2. Equal to the case of continuous operation.

3. The flicker step factor, which represents a normalized measurement of the flicker emission due to a single wind turbine switching operation, is obtained by applying the equation (4):

$$k_f(\psi_k) = \frac{1}{130}\frac{S_{k,fic}}{S_n}P_{st,fic}T_p^{0.31} \quad (4)$$

4. The voltage change factor, which represents a normalized measurement of the voltage variations due to a wind turbine switching operation, is obtained by applying equation (5), where $U_{fic,\min}$ and $U_{fic,\max}$ are, respectively, the minimum and maximum rms values taken by the fictitious grid voltage, during the switching operation.

$$k_u(\psi_k) = \sqrt{3}\frac{U_{fic,\max} - U_{fic,\min}}{U_n}\frac{S_{k,fic}}{S_n} \quad (5)$$

5. Both factors are computed, as final result, as the average value of all the obtained 3-phase values.

C. Numeric model

The stated model, based in *IEC 61000-4-15* and in *IEC 61400-21*, forms the basis of the developed computational power quality tool, which was implemented in MATLAB™ environment and is detailed in [3].

The most relevant aspect of the programming is that the data series are made of two column vectors, which can be rms currents values and voltage-current phase angles, in a low frequency analysis (frequency < 500 Hz), or voltage and current instantaneous values for high frequency analysis (frequency ≥ 500 Hz). This separation comes from the fact that it is proved that a rms values based analysis shows higher deviations than the instantaneous values based analysis sampled at more than 500 Hz, although these deviations are dependent of the power spectral density.

3. Case-Study Application and Validation

In order to validate the developed wind park power quality tool, some simulations were performed and the results were compared with experimental data gathered by a MEASNET certified institution and made available within the WIRING R&D European project (EU contract JOR3-CT98-0245) [4].

The test site was composed by a 9x225kW wind park, located at Samos Island in Greece. The available experimental data was gathered locally from the 20th to the 22nd of July 1999 and consists of seven series of measured values at WECS#1; five of the seven samples concern switching operation and the remaining two are related to continuous operation.

The base case was set with the following characteristics: $S_{cc} = 4500$ kVA (short-circuit power of the fictitious grid), $P_n = 225$ kW (WECS nominal power) and $f = 1600$ Hz (sampling frequency).

This base case situation was simulated for the seven series of measured values, in order to obtain, for each one, the previously mentioned wind park power quality performance indexes: flicker severity, P_{st}, short term flicker coefficient, $c(\Psi_k, v_a)$, voltage change factor, $k_u(\Psi_k)$ and flicker step factor, $k_f(\Psi_k)$. It should be recalled that these indexes were calculated for each grid impedance phase angle (Ψ_k = 30º, 50º, 70º, 85º) and in what concerns c, k_u and k_f, also for each wind speed distribution (wind mean speed = v_a = 6, 7.5, 8.5, 10 m/s).

The obtained results were then compared against the reference available data. To serve as an example, Figures 3 and 4 depict the achieved P_{st} relative error concerning a continuous operation related series of measured values (Fig. 3) and a switching operation related series of measured values (Fig. 4).

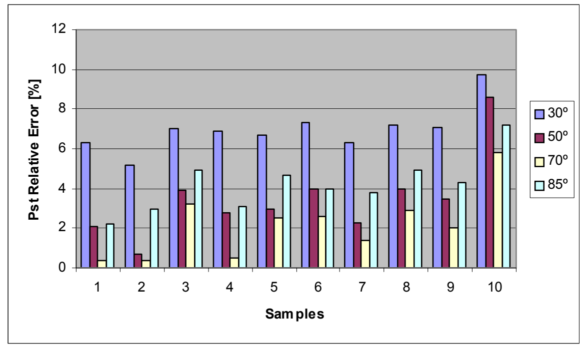

Fig. 3 – P_{st} relative error (%), continuous operation.

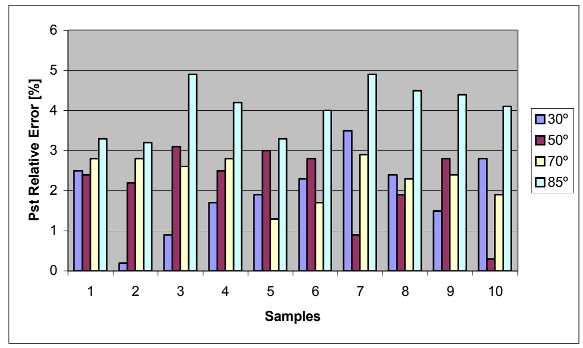

Fig. 4 – P_{st} relative error (%), switching operation.

From analysis of Figures 3 and 4, one can observe that the relative errors are always less than 10% in continuous operation, and lower than 5% in switching mode which can be considered as a good indicator in an initial stage of development of this numerical wind park power quality tool. It should be mentioned that for the other available measured series, the relative error is rarely greater than 10% and never surpasses 30%. Furthermore, the situations in which the relative errors approach 30% correspond to P_{st} values of very small magnitude. However, additional effort is required, in order to improve the developed wind park power quality tool, which is a task that is currently under way.

Further work is also needed since some adjustments in the implemented algorithm concerning the sampling frequency of 50 Hz are required, due to some detected abnormal relative errors, namely in the cases of $\Psi_k = 70º$ and $\Psi_k = 85º$.

The test procedures of the developed wind park power quality tool involved a great number of simulations, in order to examine the influence of different parameters in the power quality results. A summary of the performed simulations is depicted in Table III.

TABLE III – Summary of the software test simulations (S_{cc}: short-circuit power of the fictitious grid, P_n: WECS nominal power, f: sampling frequency).

S_{cc} (kVA)	P_n (kW)	f (Hz)
4500	225	50
3000	225	50
6000	225	50
4500	100	50
4500	500	50
4500	225	1600
4500	225	800
4500	225	400

Detailed simulation results and comments can be found in [3].

4. CONCLUSIONS

In this paper, a wind park power quality tool was presented. This tool follows the procedures recommended in International Standards *IEC 61400-21* and *IEC 61000-4-15*.

The main final output of the developed power quality software piece are the defined performance indexes: short term flicker severity, P_{st}, flicker coefficient, $c(\Psi_k, v_a)$, voltage change factor, $k_u(\Psi_k)$ and flicker step factor, $k_f(\Psi_k)$.

In order to validate the implemented algorithms, a number of simulations were performed and the results were compared with available experimental data from a certified institution, concerning the defined wind park power quality indexes.

In general terms, the comparisons showed a good agreement, which is an interesting achievement, taking into account that the development is at its initial stage. However, the results also showed that further work is required, in order to overcome some minor mismatches that still occur, namely for grid impedance angles of $\Psi_k = 70º$ and $\Psi_k = 85º$ concerning the sampling frequency range of 35 to 100 Hz.

The development of numerical power quality tools like the one presented in the paper enables – together with the use of dynamic wind park models – to assess the wind park power quality (in the feasibility phase of its project) taking into consideration the local grid conditions in a case by case approach, and making possible to avoid eventual negative impacts in the utility grid that these days are prevented, in most situations, by using restrictive "thumb rules".

References

[1] IEC/CEI 61400-21, "*Wind turbine generator systems – Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines*", Bureau Central de la IEC/CEI, 1st ed., Genéve, 2001.

[2] IEC/CEI Standard 61000-4-15, "*Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 15: Flickermeter – Functional and design specifications*", Bureau Central de la IEC/CEI, 1st ed., Genéve, 1997.

[3] Torres, P., Carneiro P., "*On the Analysis of Wind Park Power Quality*" (in Portuguese), Final Graduation Thesis, IST – Technical University of Lisbon, September 2001.

[4] Santjer, F, G. Gerdes "*Power Quality Measurements at the Wind Turbine Vestas V27 at Samos, Greece*", DEWI – German Wind Energy Institute, 2000.

[5] Sorensen, P., "*Methods for Calculation of the Flicker Contributions from Wind Turbines*", Riso-1-939(EN), Roskilde, 1995.

[6] Sorensen, P., Tande, J. O., Sondergaard, L. M., Kledal, J. D., "*Flicker Emission Levels from Wind Turbines*", Wind Engineering, Vol. 20, No. 1, 1996.

[7] Koulouvari, M., Ladakakos, P., Binopoulos, E., "*Field Test Results Concerning Wind Turbines Power Quality and Their Interaction with the Grid*", European Wind Energy Conference 1997, Dublin, Ireland, October 1997.

[8] Usaola, J., Vilar C., Amarís H., Ledesma P., Rodriguez J. L., "*Characterization of WECS Through Power Spectra for Power Quality Studies*", European Wind Energy Conference 1999, Nice, France, March 1999.

[9] Amarís, H., Vilar, C., Usaola, J., Rodríguez, J. L., "*Modeling Wind Energy Conversions Systems in the Frequency Domain for Flicker Analysis*", Wind Engineering, Vol. 23, No. 4, 1999.