POWER QUALITY MEASUREMENTS ON DIFFERENT TYPES OF WIND TURBINES OPERATING IN THE SAME WIND FARM

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ABSTRACT**.** CRES has developed a dedicated measuring system to comply with the IEC recommended practices for power quality measurements. In addition, since early in the year 2000, CRES operates its own 3.01 MW demonstration wind farm where the aforementioned practices can be implemented and verified. This study aims to reach readily comparable results from four different types of wind turbines operating in this wind farm, with a view to their power quality characteristics. For this purpose, a typical set of measurements is performed for each wind turbine, and a common evaluation method is applied, the whole approach being conducted according to the currently valid IEC standard. In this study, the measurement procedure is described in detail and the most indicative results are presented.
Keywords: Power quality, IEC 61400-21, flicker, harmonics

1. INTRODUCTION

The increasing number of wind turbines (WTs) connected to the existing electrical systems, as well as the advance in WTs power control policies, leads to the imposition of several criteria for the assessment of their impact on grid power quality. Most of these criteria are being included in IEC 61400-21, which proposes a specific measurement procedure and the corresponding methodology for assessing power quality. Being a certified body, CRES has developed a dedicated measuring system to comply with the IEC recommended practices and today has a significant presence in the power quality measurements market. In addition, since early in the year 2000, CRES operates its own 3.01 MW demonstration wind farm where the aforementioned practices can be implemented and verified.

The wind farm comprises, at the moment, four wind turbines (WTs) of different make and technology (i.e. speed and power regulation policy), one of them being a greek prototype and the other three commercially available machines. The nominal power of these WTs ranges from 500 to 750 kW. Two of the examined WTs use constant speed (CS) strategy for the connection to the main grid whereas the other two follow variable speed (VS) strategy. Another variable speed greek prototype is also installed, but it is not yet operational and will not be included in the analysis.

This study aims to identify the main power quality characteristics from the four different types of wind turbines mentioned above. For this purpose, a full set of measurements is performed for each wind turbine, and a common evaluation method is applied, the whole approach being conducted according to the currently valid IEC standard.

The measurement data have been properly selected in order to meet the minimum requirements imposed by IEC, so as to provide a common basis for the subsequent analysis. The main parameters calculated for each wind turbine type are the flicker coefficients $C(\psi_k,v_a)$ during continuous operation and the flicker step (K_f) and voltage change factors (K_u) in switching operations. The term "switching operations" corresponds to the following tests: (a) wind turbine start-up at cut-in wind speed, (b) start-up at rated wind speed and (c) switching between generators, where applicable. The above parameters are calculated as functions of network impedance phase angle and annual average wind speed, for a given grid short-circuit power at the point of common coupling (PCC) to the electrical network. Finally, calculation of harmonics up to 9 kHz has been done for each WT, including integer harmonics as well as inter-harmonics. The most indicative results of this harmonic analysis are presented, with the emphasis given in the variable speed WTs, which are expected to be the most important source of high frequency harmonic currents. The maximum total harmonic distortion as a percentage of rated current value is also calculated for each WT.

2. DESCRIPTION OF THE POWER QUALITY MEASURING SYSTEM

The system used for the power quality measurements consists of the following components:

a. Voltage transformers. They have been installed in a separate box and connected to phase bars L1, L2 and L3, respectively.
b. Current transformers. Three current clamps, one for each phase.
c. PQUAL Unit. Provides anti-aliazing protection and signal conditioning for each output from sensors of electrical system quantities (Three 8^{th} order, low-pass, anti-alias, programmable FILTER modules for connection to voltage sensors; Three 8^{th} order, low-pass, anti-alias, programmable FILTER modules for connection to current sensors). In addition, it contains a PLL-unit in combined operation with a variable frequency divider for providing the Data Acquisition System with the sampling frequency, set as a power-of-2 of the grid frequency. The available sampling frequencies are 1600, 3200, 6400, 12800, 25600 and 51200 Hz (per channel).

d. Data Acquisition System. PC-based data acquisition system (DAS) combines an A/D converter plug-in card with an interface PCB card with track and Hold (T/H) amplifiers for simultaneous sampling, controlled by the PC. The software (developed at CRES) runs on a Pentium PC under Windows NT.

In addition to the electrical parameters (voltage and current), the reference wind speed and direction have been sampled and recorded with a sampling frequency of 1 Hz.

The CRESDAQ software is continuously acquiring and storing data applying the double buffering technique for uninterrupted monitoring. In cases of high-rate sampling when the memory capacity of the PC are exceeded, the double buffering technique is not possible: instead the single-shot option is only valid, meaning that in the end of each recording interval (options for 30 sec, 1 min, 2min, 5min, 10 min, 30 min and 1 hour) the buffer is stored on the hard disk and after that the sampling resumes. In this case, successive recording intervals are separated by a time gap defined by the sampling frequency, the number of channels and the record length. For the eight channels collected the maximum attainable record length for a sampling rate of 51200 Hz (harmonics and switching conditions analysis) is 30 sec in double buffering technique mode.

A pre-defined capture matrix controls data sampling and storing. The controlling parameters in this application were the wind speed and active power. Raw data for each time interval (selectable) are organised in binary files. Due to the use of two different sampling frequencies (the meteorological quantities are sampled and stored at 1 Hz), two raw files are produced for every averaging interval and code-named according to date and time. Basic statistics (the average value, the standard deviation, the maximum and minimum value) of each channel are stored every 10-minutes in ASCII files (one for each day). Flicker or harmonics calculations may be selected and the results are stored in separate ASCII files. The on-line calculations are carried on the expense of extra time-gap between successive recording intervals.

Additional features of the CRESDAQ software include real-time graphs and replaying last step time series and estimation of power spectra in parallel with the acquisition. In off-acquisition mode, any recorded time series may be viewed along with its statistics (minimum, maximum, standard deviation and average value) and the power spectrum.

3. METHODOLOGY OF ANALYSIS

3.1 Data selection

From the total amount of data collected, those that correspond to the following cases are not used in the analysis:

- The wind turbine is not operating (except for data collected during the switching operations of the wind turbine). During continuous operation under low wind speeds, all available records are examined in detail in order to exclude successive cut-in and cut-off operations.
- Any of the measurement instruments out of order.

3.2 Calculation of parameters

The power quality parameters are evaluated during post-processing from the collected voltage and current time-series. The analysis is based on dedicated software developed at CRES for the calculation of all the critical parameters required by the currently valid IEC standard [1]. The methodology of analysis is briefly described in the following:

(a) Flicker analysis

In order to achieve test results, which are independent of the grid conditions at the test site, IEC 61400-21 specifies a method that uses current and voltage time-series measured at the wind turbine terminals to simulate the voltage fluctuations on a fictitious grid with no source of voltage fluctuations other than the wind turbine.

It is based on 10 min records when the wind turbine is in continuous power production mode. The flicker P_{st} parameter is calculated for each phase and for several grid impedance angles. The assumed grid short circuit power for the examined site is 115 MVA. The flicker coefficient c(ψk) is determined for each of the calculated P_{st} values by applying:

$$c(\psi_k) = P_{st} \cdot \frac{S_{k,fic}}{S_n} \tag{1}$$

where: S_n is the rated apparent power of the wind turbine and $S_{k,fic}$ is the short-circuit apparent power of the fictitious grid.

In the present study, using the weighting procedure and methodology of [1], the flicker coefficients $c(\psi_k, v_a)$ are determined as the 99th percentile for the network impedance phase angles ψ_k=15°, 30°, 40°, 50°, 60°, 70° and 85° in a table for four different wind speed distributions with annual average wind speed v_a= 6, 7.5, 8.5 and 10 m/s respectively. The 10 minutes average values of the wind speed are assumed to be Rayleigh distributed.

(b) Switching operations

Voltage and current transients were measured during the switching operations of the wind turbine (start-up at cut-in wind speed and start-up at rated wind speed). The corresponding time series were manually triggered and recorded during site visits. Each time series was searched to locate the start of the event under consideration before evaluating the required parameters.

For both types of switching operations, the following parameters are stated:

1) The flicker step factor $k_f(\psi_k)$ for the network impedance phase angles ψ_k=30°, 50°, 70° and 85°.

2) The voltage change factor $k_u(\psi_k)$ for the network impedance phase angles ψ_k=30°, 50°, 70° and 85°.

As defined in ([1]), the flicker step factor is a normalised measure of flicker emission due to a single wind turbine switching. It is calculated according to the following equation:

$$k_f(\psi_k) = \frac{1}{130} \cdot \frac{S_{k,fic}}{S_n} \cdot P_{st} \cdot T_p^{0,31} \qquad (2)$$

where T_p is a defined time interval (in seconds) during which, the transient of the switching operation has abated.

The voltage change factor is a normalised voltage change due to a switching operation of the wind turbine and is calculated by:

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

The resulting flicker step and voltage change factors are the average of each single value calculated for each switching and each of the three phases.

(c) Harmonic analysis

The harmonic analysis is performed with the FFT algorithm. Rectangular windows of 8 cycles of the fundamental frequency width, with no gap and no overlapping between successive windows are applied. The FFT algorithm is applied on integer number of the fundamental frequency cycles due to the sampling frequency steadily adjusted to the fundamental, so no leakage effect is expected. The sampling frequency is set to 51.2 kHz, more than 4 times the cut-off frequency of the low-pass filters to reduce aliasing effects.

The data used for the harmonics analysis are voltage and current time series with a record length equal to 2 min. The integer and the inter-harmonics are calculated up to the 180th order, according to the user specification and the sampling frequency of the measurement. Furthermore, the current total harmonic distortion (THD) is calculated up to the 50th harmonic order, as shown in the following equation:

$$THD = \sqrt{\sum_{i=2}^{50} \left(\frac{I_i}{I_n}\right)^2} \qquad (4)$$

4. SITE DESCRIPTION

The site lies in southeast part of Attiki near the town of Lavrio. Obstacles to be taken into account are three operating wind turbines to the southeast. There is no relevant wind obstacle other than wind turbines in the vicinity of the test wind turbine.

The surrounding topography is complex. A topographical map of the site is presented in Figure 1. Wind turbine No 4, is not in operation and it has not been taken into account in the subsequent analysis.

Figure 1: Site map of CRES wind farm

The wind turbines are connected to a 20 kV / 50 Hz medium voltage power system through separate step-up transformers.

5. TEST CONDITIONS

During the measurements, the voltage at the wind turbine terminals was within $\pm 10\%$ of its nominal voltage as 10 min average data. It can be assumed that the grid frequency change is below $\pm 1\%$. The maximum measured 0.2 sec voltage unbalance factor was 0.92 %, calculated according to [5].

The measurements of the electrical quantities were made at the wind turbine terminals, before the voltage transformation step-up to the voltage level of the grid.

Table 1 shows the sampling frequency and the record duration for each type of measurement.

Table 1: Measurement set-up.

Measurement Type	Sampling Frequency (Hz)	Record duration (min)
Flicker at continuous operation	1600	10
Harmonics at continuous operation	51200	2
Flicker at start up (for constant speed WTs)	51200	1
Flicker at start up (for variable speed WTs)	51200	2

The measurements were performed during different time periods for each WT. The recorded time series during continuous operation of the wind turbine are summarized in Table 2. Table 3 provides the number of time-series associated with switching operations, which refer to wind turbine start at cut-in and rated wind speed. Finally, Table 4 presents the number of records used for the harmonic analysis, for active power range between 0 and 100% of the WT nominal power.

Table 2: Number of measurements for each speed bin at a sampling frequency of 1600 Hz

Wind speed bin range (m/sec)	**Number of 10-min records**			
	VS No1	**VS No2**	**CS No1**	**CS No2**
3.5 – 4.5	3	-	-	30
4.5 – 5.5	3	-	-	29
5.5 – 6.5	30	3	-	87
6.5 – 7.5	141	-	26	60
7.5 – 8.5	96	3	105	60
8.5 – 9.5	84	-	149	66
9.5 – 10.5	128	10	97	42
10.5 – 11.5	117	24	69	30
11.5 – 12.5	117	30	58	30
12.5 – 13.5	87	32	38	43
13.5 –14.5	84	23	3	59
14.5 – 15.5	102	3	-	35
15.5 – 16.5	66	23	-	40
Total Number of Records	**1058**	**151**	**545**	**611**

Table 3: Number of recorded transient events at sampling frequency of 51200 Hz

WT Type	***Switching Type***	***Number of records***
CS WT No1	Start-up at cut-in wind speed	2
CS WT No1	Start-up at rated wind speed	2
CS WT No2	Start-up at cut-in wind speed	2
CS WT No2	Start-up at rated wind speed	2
VS WT No1	Start-up at rated wind speed	1
VS WT No2	Start-up at rated wind speed	2

Table 4: Number of measurements from 0 to 100% of nominal power at a sampling frequency of 51200 Hz

	Number of 2-min records			
Output power bin (% of P_n)	**CS WT No1**	**CS WT No2**	**VS WT No1**	**VS WT No2**
0 – 100	21	27	87	24

6. APPLICATION RESULTS

The results are presented from two different points of view. The application of various technologies is studied first in terms of power quality characteristics and comparative results are presented in order to underline their individual impact on the electrical power system. These results are used for the estimation of the power quality of the total produced power, whereas important conclusions are drawn for the control system design and operation of the prototype WT. Secondly, the experience gained by applying the same measurement procedure under common test conditions is documented and used as a reference point to comment on the IEC 61400-21 proposed methodology.

(a) Flicker analysis

In Figures 2 and 3, some indicative results of the flicker analysis are presented. In Figure 2 the normalised flicker coefficient C(ψk,va) is presented for each individual WT as a function of network impedance angle for a considered annual mean wind speed equal to 6 m/s. From this diagram, it is deduced that the flicker coefficient is much dependent on network impedance angle. In fact, the calculation of flicker includes the estimation of flicker relevant phase angle ϕ_f, thus it is expected to be different for each WT as the sum $\psi_k+\phi_f$ may vary between 0 and 180^o.

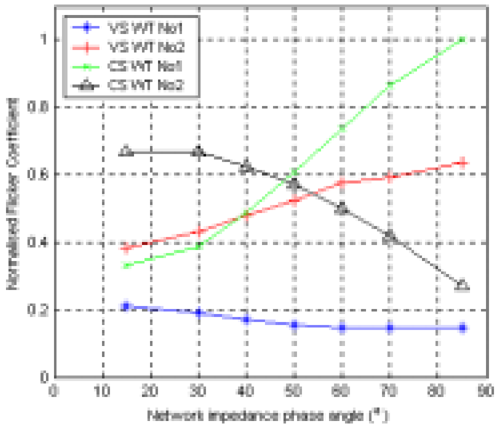

Figure 2: Flicker coefficients as a function of network impedance phase angles for the all the WTs.

In Figure 3, some indicative results of the calculated flicker coefficient c are displayed calculated from wind speed time series in all wind bins between 3.5 and 18 m/s. It is worth noting that the number of the acquired measurement records of CS WT No1 and VS WT No2, do not fulfill the minimum IEC requirements. Consequently, the results for these two WTs may change if more records are taken into account. Especially, for the greek prototype variable speed WT (VS No2), several wind bins in low wind speeds are not completed due to the fact that the turbine was not in operation for a critical time period because of modifications in the mechanical system. This means that the corresponding normalized flicker coefficients of Figure 2, are overestimated, as it is expected to have lower values in lower wind speed bins.

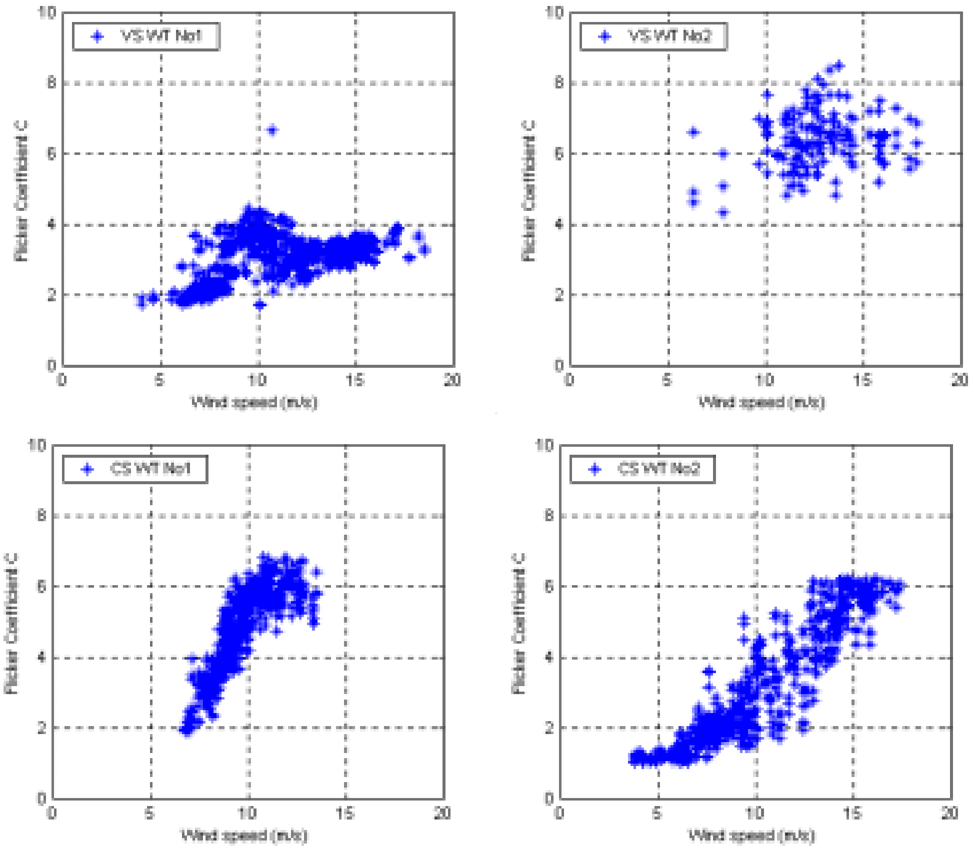

Figure 3: Flicker coefficients as a function of wind speed for all the WTs

(b) Switching operations

The flicker analysis of switching operations was based on the data given in Table 3 using a 1-min (for CS WTs) and 2-min record length (for VS WTs). The start-ups at cut-in and rated wind speed were manually recorded during site visits of CRES personnel to the wind farm, whereas the sampling frequency of the measurements has been selected to be 51.2 kHz. The flicker step and voltage change factors have been evaluated for each available switching time-series for four network impedance phase angles, according to the methodology described in 3.2. For these calculations, the duration of the switching events has been properly selected to ensure that the transient has abated, as required in [1].

In Figure 4, the calculated flicker step factors K_f and voltage change factors K_u are presented for start-up at rated wind speed, as functions of the network impedance angle. The K_f variations are similar to those during continuous operation. Therefore, even in this case the final flicker parameters are dependent on the flicker relevant phase angle of each individual turbine. The values of K_u, which denote the maximum voltage change during the start-up procedure, are lower in variable speed wind turbines, where the transient duration is larger. The latter, is illustrated in Figures 5 and 6 where the switching operation at rated wind speed is presented for two of tested wind turbines. The variable speed start-up procedure requires longer time period than the constant speed one. More specifically, the VS WT reaches its nominal power gradually after 60 seconds from cut-in, whereas the CS WT in less than 30 seconds.

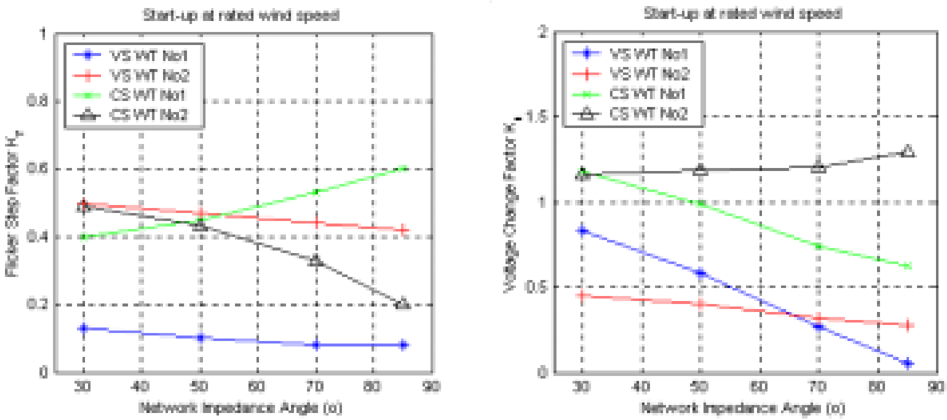

Figure 4: Flicker Step Factor and Voltage Change Factor for each WT, as a function of network impedance phase angles

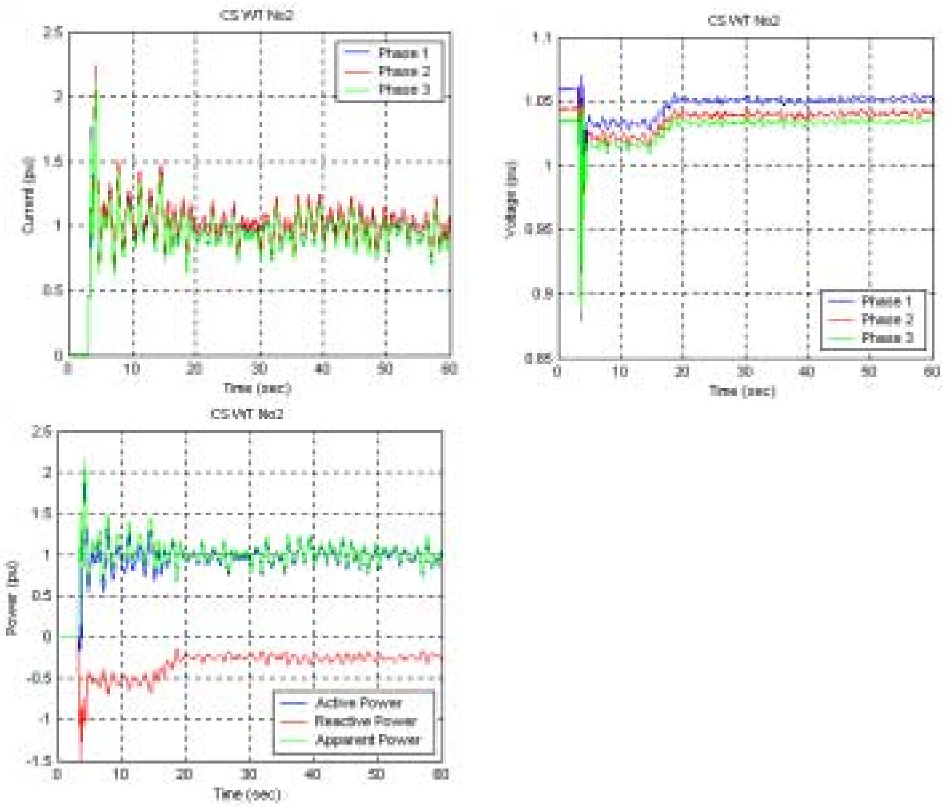

Figure 5: Constant speed wind turbine start-up at rated wind speed

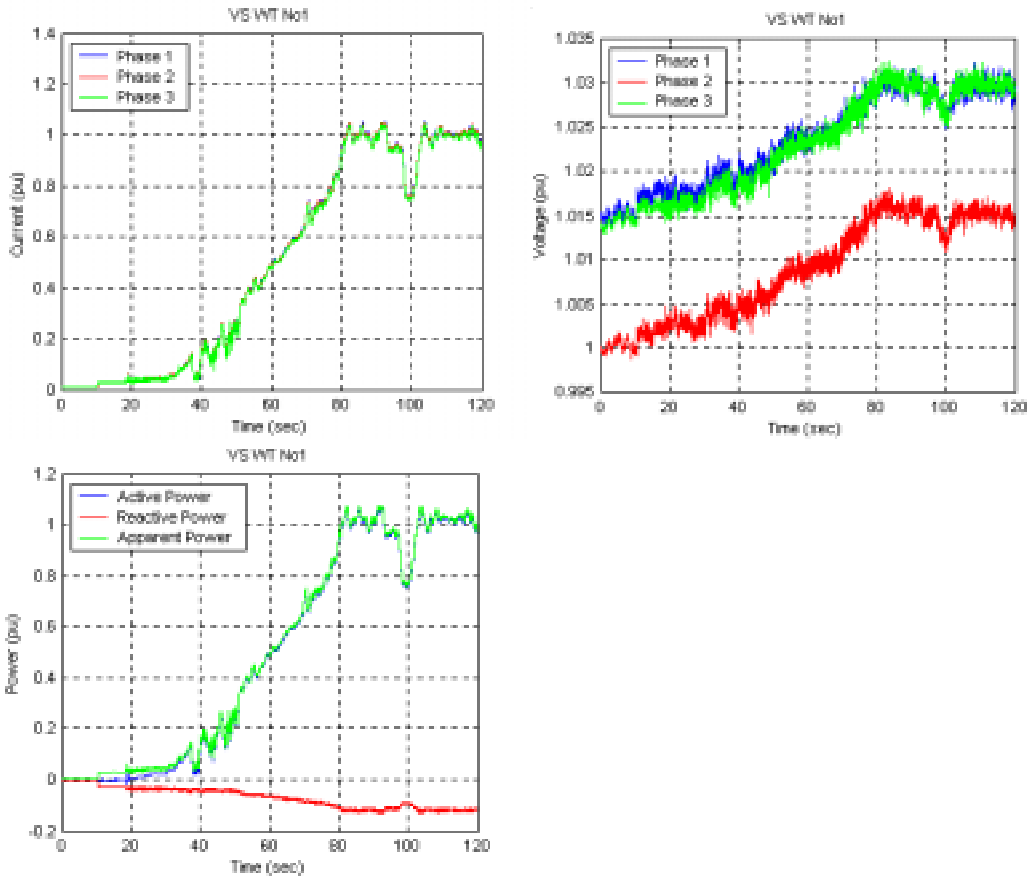

Figure 6: Variable speed wind turbine start-up at rated wind speed

(c) Harmonic analysis

Harmonic analysis has been performed up to the frequency of 9 kHz applying FFT algorithm on two-minute records with a sampling frequency of 51.2 kHz. According to reference [1], harmonic analysis is not obligatory for wind turbines directly coupled to the main grid. In the present study this was confirmed by calculating harmonic currents of both constant speed wind turbines, which are directly coupled during continuous operation. Some indicative results are presented in Figures 7 – 11. Figures 7 and 8, illustrate integer harmonic currents up to 50^{th} order of all wind turbines. It is worth noting that, directly connected WTs appear to produce high odd harmonic currents in low frequencies from 3^{rd} to 13^{th} order. On the other hand, converter coupled WTs exhibit different behaviour with regard to harmonic effects. As it is indicated in figures 7 and 9, the amplitudes of harmonics are higher over the entire frequency spectrum up to 9 kHz. The harmonic content of the directly coupled WTs is omitted because it is negligible.

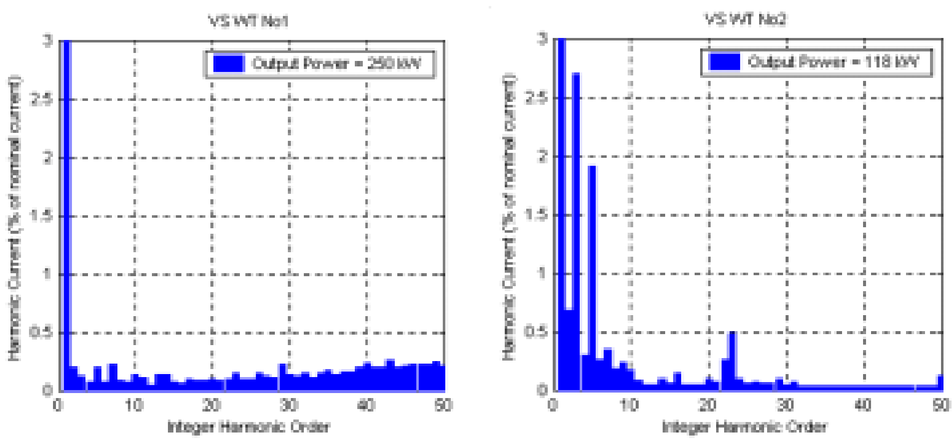

Figure 7: Phase-1 integer harmonic amplitude of the variable speed wind turbines

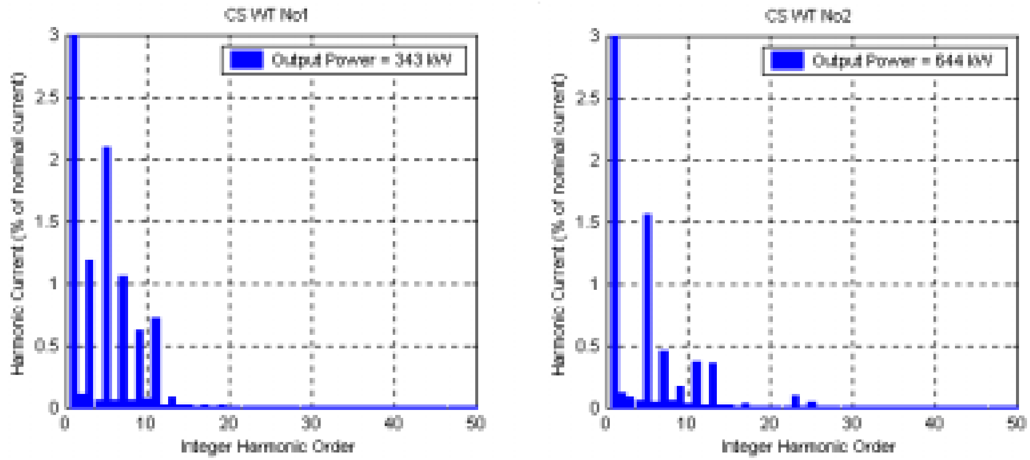

Figure 8: Phase-1 integer harmonic amplitude for the constant speed WTs

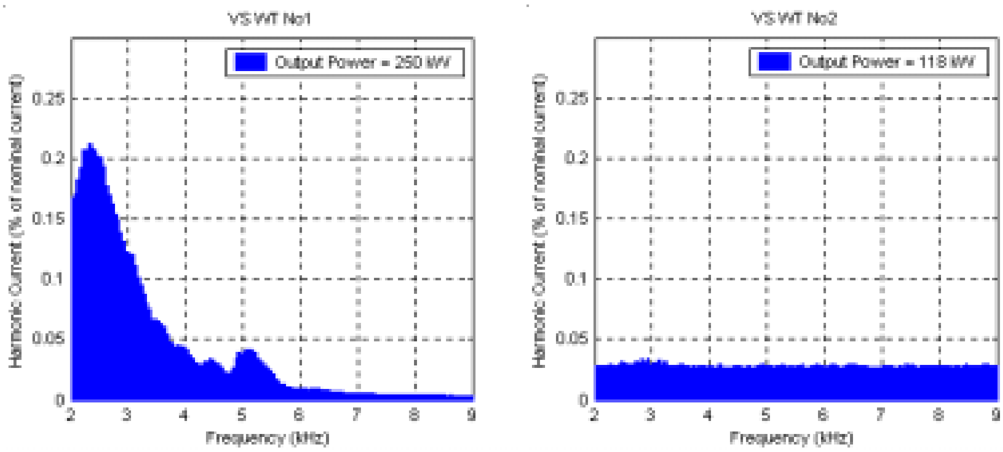

Figure 9: Phase-1 integer and inter-harmonic currents from 2 to 9 kHz for the variable speed WTs

In Figures 10 and 11 the total harmonic distortion of the harmonic currents of each WT is presented calculated according to equation (4). The results of these four diagrams are comparable. This is explained by the fact that directly coupled WTs contain higher harmonic amplitudes in the low frequency range as it is already mentioned. Another comment on these results is that, in general, THD is slightly reduced at high output powers close to nominal. In order to have a better understanding of this behaviour, a sufficient number of harmonic records are required for WT operation in all bins of power between 0 and nominal.

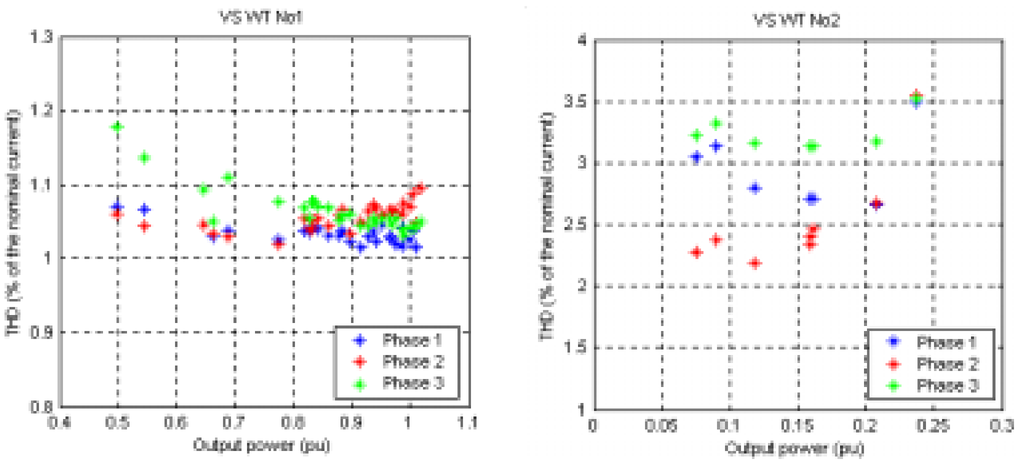

Figure 10: Total harmonic distortion as a percentage of nominal machine current vs active power for the variable speed WTs

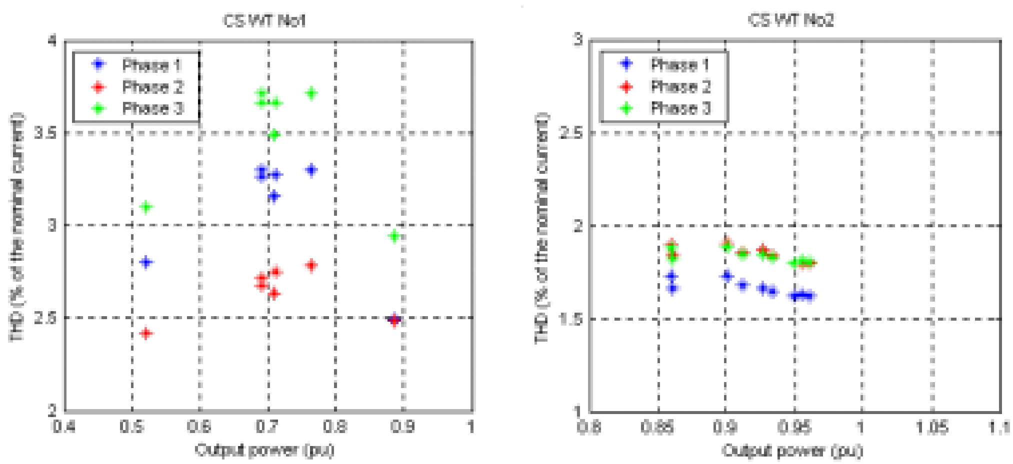

Figure 11: Total harmonic distortion as a percentage of nominal machine current vs active power for the constant speed WTs

7. CONCLUSIONS

The main conclusions of the present study can be divided into two parts:

The first part is related to the power quality characteristics of the examined wind turbines connected to a large power system. In continuous operation, all WTs have common flicker characteristics, although a larger number of records are required for two of them. During switching operations, a different way of coupling is adopted from each type of WT. However, differences between flicker step factors K_f and voltage change factors K_u are not significant. Finally, harmonic analysis results did not show any abnormal behavior of the examined WTs. A more detailed measurement campaign should be performed on the greek prototype VS WT, since several tests are still in progress.

In the second part some comments on the power quality measurement campaign suggested by IEC can be done. First of all it should be mentioned that uncompleted wind speed bins may lead to uncertain deviations in the calculation of flicker coefficients. On the other hand records in wind speed bin between 3.5 and 4.5 m/s may include transients due to WT cut-in, and should be closely investigated. Wind direction does not seem to play very significant role in flicker estimation, especially during switching operations and harmonic analysis, as far as major obstacles are concerned. Finally, flicker coefficient does not seem to be significantly varying with turbulence intensity provided that turbulence is kept within acceptable limits during the tests.
For the assessment of the calculated power quality parameters, the total flicker emission should be estimated at the central bus of the wind farm, according to the individual parameters of each wind turbine. However this assessment was outside the scope of the present study.

8. REFERENCES

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