An Experimental Study on Power Quality of Wind Turbines

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Abstract
This paper shows a study on Power Quality (PQ) analysis of Wind Turbines (WT) installed in wind farms. The measurement system used was proved very useful and its flexibility has made possible to make some dynamic studies, which require a fast and synchronised measure. It has been installed in three wind farms with three different types of asynchronous generators of 600 kW and 700 kW classes.

- Conventional, squirrel cage induction generator directly connected and with fixed pitch (SQIG).
- Wound rotor, induction generator with external variable resistance and variable pitch (VRIG).
- Doubly fed asynchronous generator with external variable resistance and variable pitch (DFIG).

The first part shows static relationships among active and reactive power, voltage drops and harmonics; with data derived from 1 min and 10 min measures. These integrating periods allow studying stationary behaviour and power performance of the turbine. One advantage of these measuring periods is the smoothing effect that filters oscillations and noise present in wind and in other signals.

In the second part, a dynamic study has been performed, focused on transients, connection and disconnection events and power fluctuations. Transient events such as connection of capacitor banks are studied with the waveforms. The firing of thyristors during soft start is also studied through waveforms. The whole evolution during the connection of the generator is analyzed through the RMS value of each cycle of the grid because it is a longer transient. Power fluctuations are also studied through values of current and power each cycle or half-cycle.

I. INTRODUCTION

To accomplish the PQ static analysis, average values of 1 to 10 minutes are measured at WT and substation. These data can be easily obtained from the data-logger of the meteorological tower and from electrical network analysers.
Notwithstanding this fact, long measuring intervals have some drawbacks. Transients are neglected. Some effects like power fluctuations and current inrush at connection or disconnection can only be seen if shorter integrating periods are employed. In some cases, RMS or mean values are measures not quick enough, so some studies require the availability of waveforms or instantaneous values.

The switching events can be clearly noticed in the WT, but the effect in the substation of the park is quite weak. This is mainly due to the independent operation of the WT in a farm and the diverse wind conditions that each WT experiences. Power fluctuations due to tower shadow and wind shear are studied through the frequency analysis. The power and the current present slow fluctuations, and they are spread in wide frequency bands.
There is a small probability that a turbine enters in a resonance or that the blades of some turbines pass in front of the tower synchronized. A time-frequency analysis has been performed to detect a possible resonance.

II. MEASUREMENT SYSTEM

Most of the available supply network analysers do not allow either the recording of signals at high sampling rate for long periods or complex calculus with the acquired data. This can be a burden when performing a dynamic analysis.
The Electrical Engineering Department of the University of Zaragoza and CIRCE Foundation have developed a measurement system for dynamic analysis [1]. A PC computer, an acquisition board and signal conditioning modules compose the main system.

It can be placed in the low voltage side of a WT or connected to the measuring transformers of the wind farm substation. On the one hand, the effect of starting, stopping and power oscillations (due mainly to tower shadow and wind shear) is more easily studied locally at a single WT with waveforms or fast measures. On the other hand, the global effect of all WT should be analysed at the output of the wind farm (statistical dispersion of events and partial compensation of fluctuations play a key role in the overall behaviour of the system) [2].

The measurement system was installed in two wind farms owned by CEASA with wind turbines in the 600 kW class. Both farms have wound rotor asynchronous generators and variable pitch. One farm has wound rotor induction generators with a variable resistor connected to their rotor (VRIG), from Vestas. This fact makes generator speed vary from 1500 to 1560 rpm. The other one utilise doubly fed induction generators (DFIG) from Gamesa, with generator speed from 1220 to 1620 rpm.

It was also installed in a wind farm with wind turbines in the 600 and 750 kW class and with fixed pitch (stall control). The utilized generators are squirrel cage induction generators (SQIG), one speed, directly connected to the network. The 600 kW WT has one generator, with one fixed speed (1500 to 1514 rpm). The 750 kW wind turbine employs a secondary 200 kW generator to increase production at low wind by reducing rotor speed (1000-1006 rpm versus 1500-1510 rpm).

In addition to the measures achieved at the turbines, the system has been placed in the substation of the farm. This has made possible to study the overall effect of all the turbines of a park in the point of common coupling (PCC). Substation parameters are measured at voltage and current transformers.

III. STATIC ANALYSIS

A. HARMONICS

On the studied cases, harmonics are only noticeable in the turbine with electronic power converters or at switching events. Switching events can generate noticeable transitory harmonics, but the standard IEC61400-21 don't consider them.

Power converters of DFIG turbine produce high frequency harmonics in voltage during continuous operation. Current THD can be noticeable at low output powers because it is a measure relative to fundamental current. However, absolute values of distortion are not very dependent on power output in continuous operation. The main effect of these harmonics is related to interference with signals and electronic devices (apart from the increase of losses in magnetic cores and capacitors, circulation of currents through bearings of generators…). The high frequency harmonics, corresponding to the switching of IGBT around 8 kHz, are only of importance inside the turbine, because they are largely filtered by the high impedance of transformers at such frequencies (and, in second place, capacitance of cables) [3]. These harmonics are not in phase from one turbine to another, so they partially cancel and they don't affect the grid in the analyzed grids.

However, electronic converters based on slower devices can generate harmonics of lower frequencies and hence, harder to block, allowing the excitation of resonances at farer points. At substation, only low order harmonics (3, 5, 7 and surprisingly 2, 4) have been found. In one farm where this effect was remarkable, the presence of even harmonics is confirmed in the waveforms, which were not symmetrical. This can be the origin of some random firing of homopolar voltage protection at the substation. This has happened even with still turbines, so this fact has been attributed to the topology of the grid, with the farm at the end of a long line with many consumers.

B. VOLTAGE VARIATIONS

In Fig. 2, there is a clear relationship of voltage with power output at WT LV side due to high short circuit impedance Zk after substation transformer and cables (power transmission from WT to substation is made at 690 V, so Zk is quite resistive). In the other studied cases, where a MV network was employed to connect the turbines with the substation, it was no evident relation between active power output and voltage at the substation (the compensation of reactive power takes place in the turbine, so the inductance of transformers and lines only affects appreciably during switching events, where the current is quite reactive).

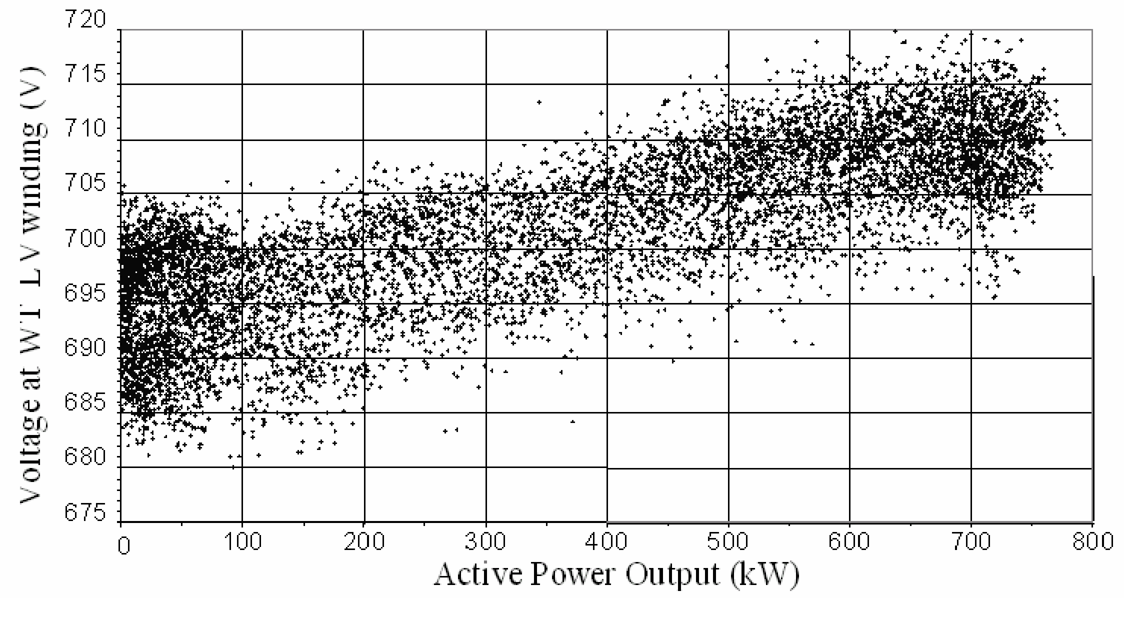

Fig. 2: Voltage versus power output at a SQIG WT connected to a quite resistive line.

According to this fact, major voltage fluctuations at substation are essentially due to the resistance of conductors, other consumers of reactive power, changes of topology and manoeuvres, especially in long distribution lines. In some sites, the influence of active power in voltage is very weak even for measures at LV winding of a WT owing to short circuit impedance Zk angle near 90º (there is a transformer in the WT and cable lines are not too long).

For the studied cases, where wind power is small compared with the loads, the influence of wind farm is usually low. Thus, the rest of the grid masks possible affections of wind power to the voltage. Therefore, the main problem related to static voltage analysis is to obtain representative data of the grid at key points; otherwise relationship between wind farm active and reactive power and voltage is so fuzzy and blurred that no relationship can be stated.

C. REACTIVE POWER

Present regulation at Spain demands and rewards unit power factor at substation. SQIG and VRIG WT need capacitor banks to compensate inductive reactive power consumed by generator. In most WT models with capacitor banks, they are sized to nearly compensate reactive power. At low capacity factors, capacitor can fully compensate reactive, but at higher loads, the WT consumes inductive reactive power.

At around cut-in wind speed, power factor at wind farm is low. This is due to the high inductive current at connection. This current is gradually compensated until all needed capacitor banks are connected (this can require between 15 s and 1 min, depending on the control of the WT). In addition, the capacitor banks are disconnected some cycles before the generator to avoid its self-excitation (that could lead to dangerous over voltages). As connection is a slower event than disconnection, connection has greater effect in the overall reactive behaviour of the farm.

Active/reactive curves of a VRIG and of a SQIG are similar. In the WT analysed, VRIG has higher rotor resistance than SQIG, especially near nominal power. Measured reactive power confirms that static equivalent model circuit of induction generator is accurate enough for static simulations [4].

One problem that arises with capacitor banks if wind speed is not very steady is that it can lead to frequent switching of capacitor banks. Apart from the apparition of transitory events in waveforms, frequent switching decreases overall power factor: if reactive power consumed by generator varies considerably, power factor correction would try to follow theses variations. However, as the frequency of switching is limited by the control of capacitor banks, compensation level will be reduced because it is not quick enough (see fig. 2).

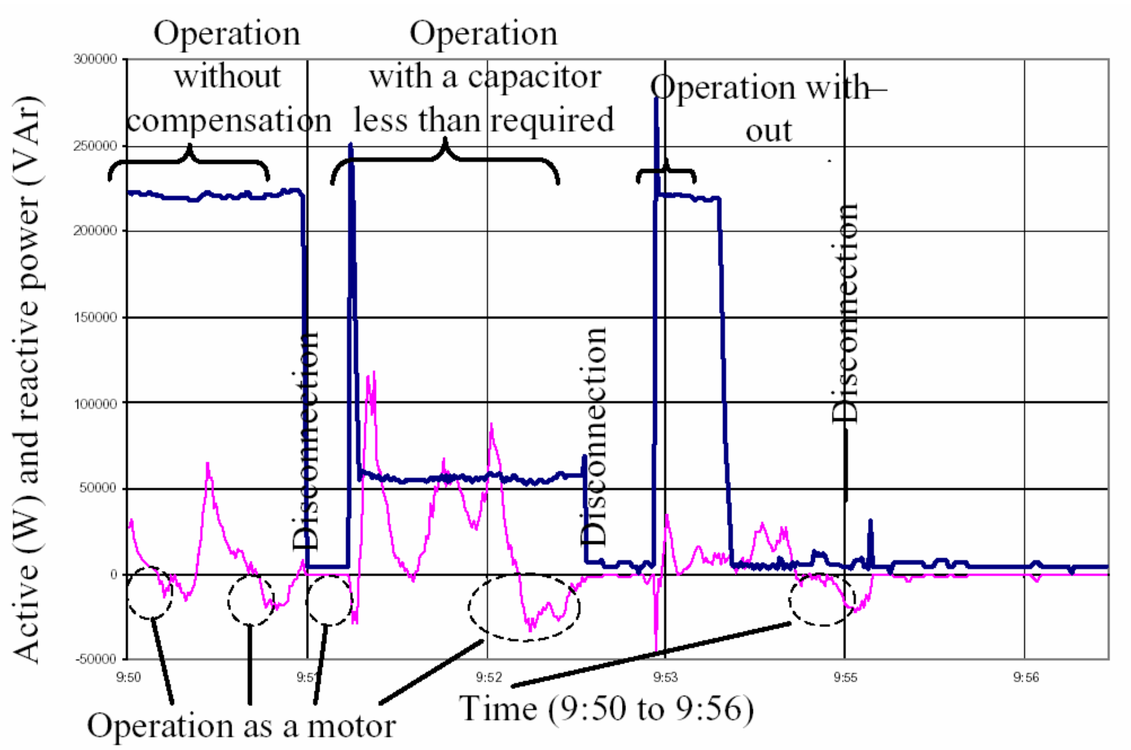

Fig. 2: Active and reactive power of a VRIG WT along the time (1 min averages).

IV. DYNAMIC ANALYSIS

A. TRANSIENT EVENTS

A.1 Thyristor soft start (connection of generator)

In Fig. 3, the intensity of current is shown during the connection. The conduction angle is increased from an initial value up to 180º, then the contactor that short-circuit thyristor is closed about ½ or 1 second after the start (depending on the WT). At that moment, the slip of a SQIG is small and the generator continues accelerating for a while, until the equilibrium between the mechanical torque from the turbine and the electrical torque of the generator is reached. During connection, inrush current can reach the double of nominal value in SQIG with fixed blades.

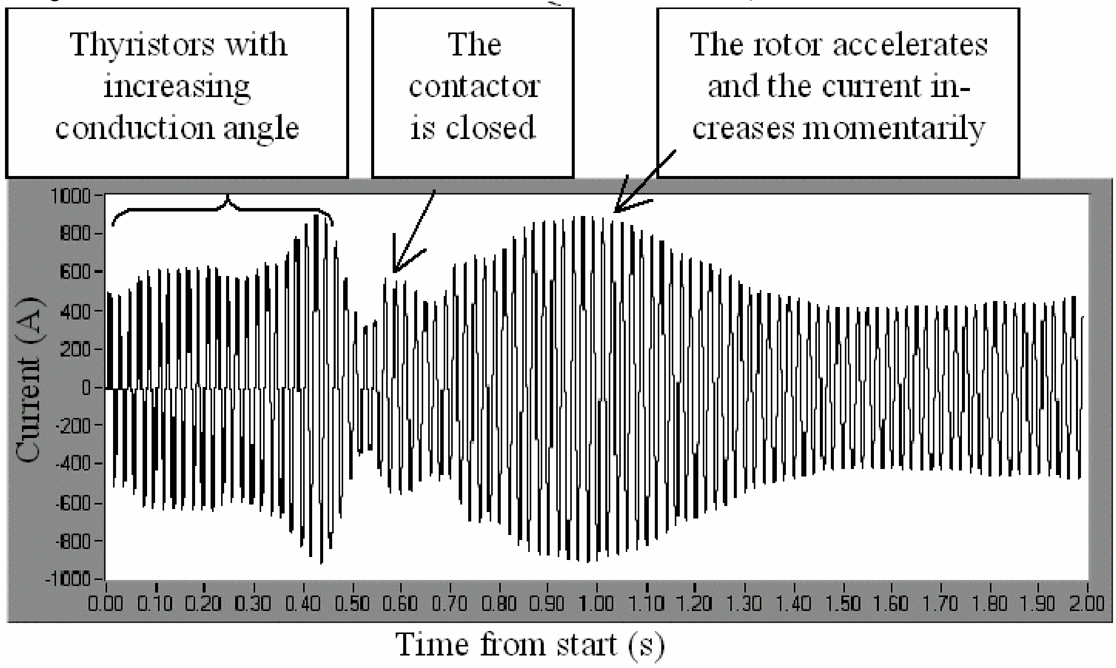

Fig. 3: Intensity of current during the connection of SQIG.

The softest connection is in VRIG, since the generator and blade control achieve a very low inrush current. The rotor currents injected through the slip rings achieve the magnetization of the generator. The IGBT converter provides the magnetizing current without reactive consumption from the grid.

A.2 Disconnection of generator

The disconnection also generates small voltage sags, since the capacitor bank is disconnected before the generator to avoid self-excitation. In Fig. 4, VRIG is softly disconnected reducing the conduction angle of the thyristors.

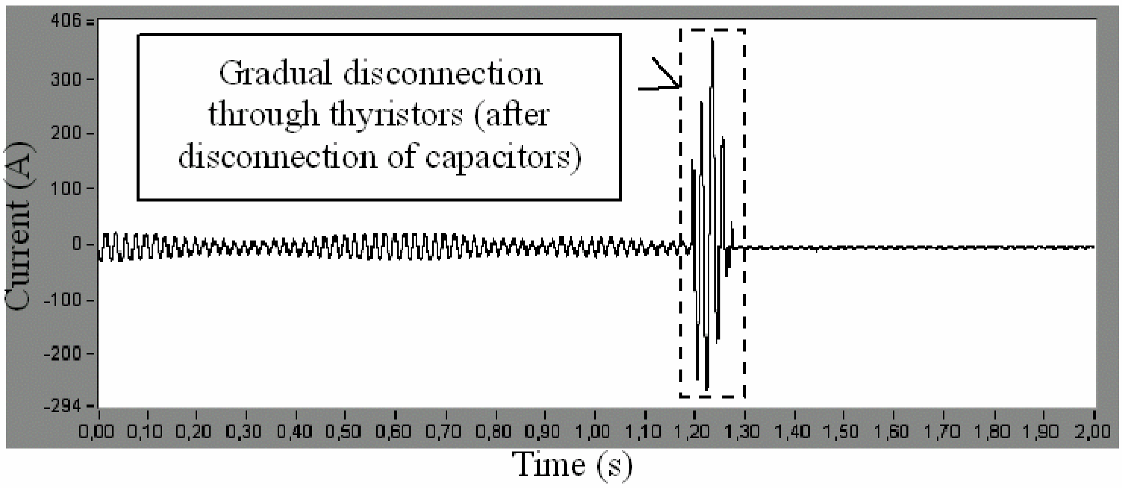

Fig. 4: Current waveform at VRIG during a disconnection.

In the DFIG, the electronic converter is disconnected before the generator. In this turbine, the generator is directly disconnected simply opening the contactor of the generator (the soft-start thyristors are not used during disconnection). Fig. 5 shows this small sag due to the reactive disconnection current that is only noticeable at the low voltage winding of the transformer (around 5 % of voltage drop).

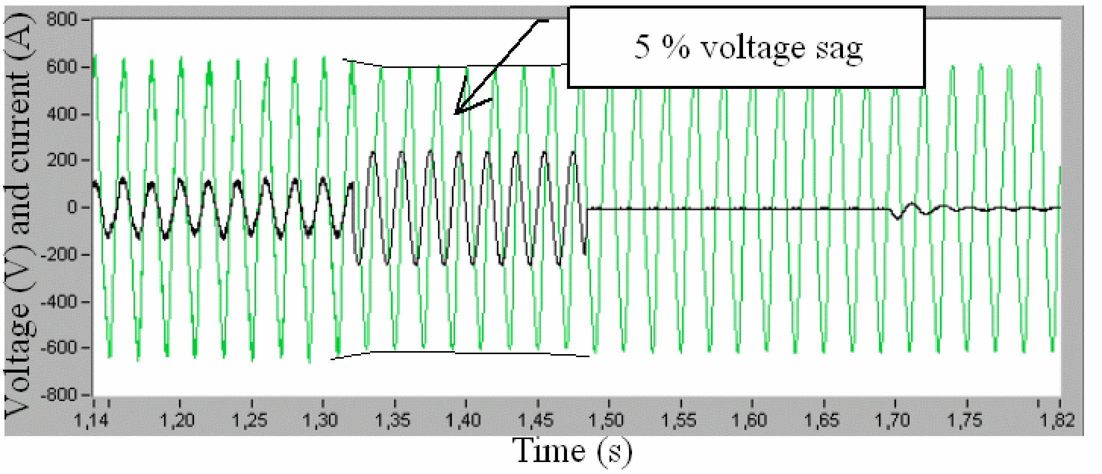

Fig. 5: Current (black) and voltage (grey/green) waveforms at DFIG during a disconnection.

A.3 Switching of capacitor banks

Fig. 6 shows RMS values of current in a connection of a VRIG. Current at connection is very reactive and causes 2.5 % of voltage drop in WT although it cannot be seen in the substation. After 0.6 seconds, the soft start finishes and thyristors are short-circuited. After 2 s, the first capacitor (62.5 kVAr) is connected, and then the second one (62.5 kVAr), third one (50 kVAr) and forth one (50 kVAr) with a lapse of 1 s. After 6.6 s, the whole capacitor bank is connected and voltage in WT is restored.

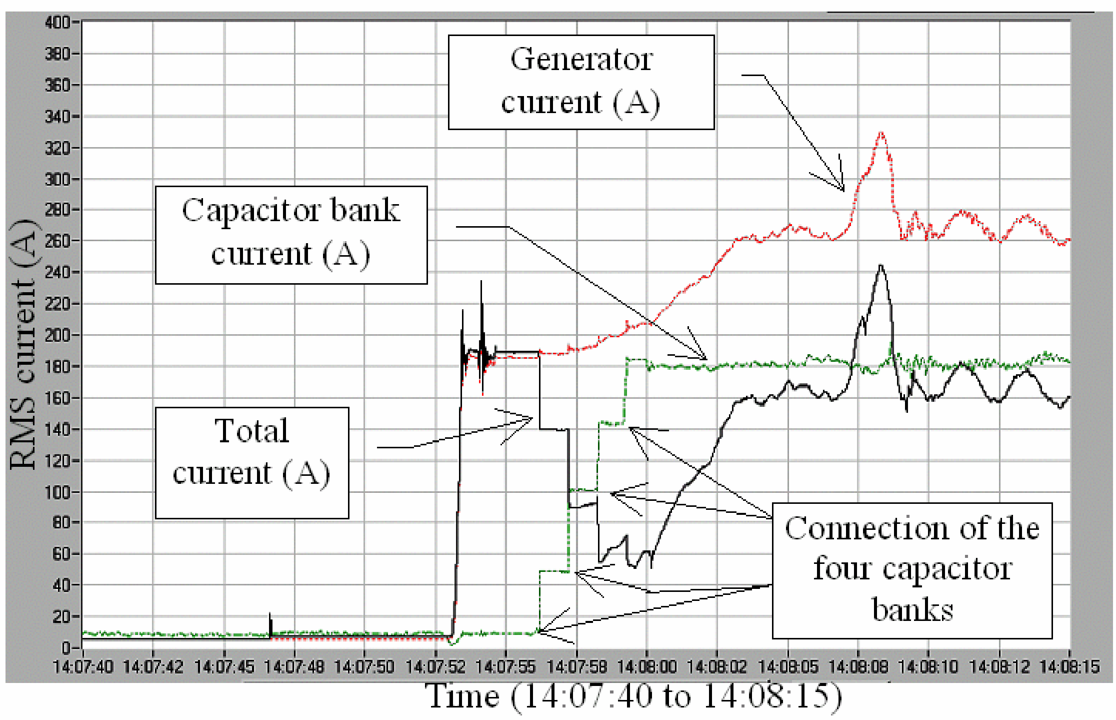

Fig. 6: Phase-to-neutral voltage, current and power during the connection of VRIG.

V. CONCLUSION

A methodology for power quality analysis has been developed for wind farms and wind turbines. One part of the work corresponds to steady state analysis, comparing average of the main parameters of a wind farm and its wind turbines to assess possible relationship among them. The studied parameters have been power curve, stationary harmonics, voltage and its variation and reactive power. The employed measurement system was proved very useful and its flexibility has made possible to make some dynamic studies, which require a fast and synchronised measure.

The operation of WT with more common technologies has been compared from the network point of view. In addition to this, the impact of a single WT is compared with the farm where it is installed. The measured data show that harmonics and voltage are correlated with operation parameters of a WT –at low voltage winding–, but relationship is very weak at substation due to the high fault level of PCC, filtering of transformers and cables, the influence of other consumers outside the farm and changes of network topology.

The impact of wind farms in voltage is low, since reactive power is low due to actual regulation. As resistive component of short circuit impedance is low in studied sites, the variations of voltage are mainly exogenous. Only is the affection of voltage important in weak networks with quite resistive networks or when current is quite reactive.

The high level inter-harmonics of DFIG only affect significantly devices inside the WT. These inter-harmonics are not in phase among the turbines and they are largely blocked by inductances and they did not appear at substation. Fluctuations at power and current output of studied substations are low, fluctuations are low at voltage and they do not originate flicker levels of significance, at least at the farms analyzed. Joint time-frequency analysis has been applied to the power generated by WT and confirmed that fluctuations are stronger at connection and at other transients. The fluctuations reach a steady value at normal operation and no special resonance conditions have been found up to now.

REFERENCES

[1]M. Sanz, A. Llombart, Á. A. Bayod, J. Mur, "Power Quality Measurements and Analysis for Wind Turbines" IEEE Instrumentation and Measurement Technical Conference, IMTC 2000, pp. 1167-1172.
[2]G. McNerney, R. Richardson, "The statistical smoothing of power delivered to utilities by multiple wind turbines," IEEE Transactions on Energy Conversion, Vol. 7, No. 4, pp. 644-647, Dec. 1992.
[3]Heier, Siegfried. "Grid integration of wind energy conversion systems". John Wiley & Sons Ltd.
[4] Andrés E. Feijoo, J. Cidrás, J.L.G. Dórenlas, "Wind speed simulation in wind farms for steady-state security assessment of electrical power systems", IEEE Trans, on Energy Conv., Vol. 14, No 4, Dec. 1999, pp 1582-1588.