Research Journal of Applied Sciences, Engineering and Technology 4(5): 433-438, 2012
ISSN: 2040-7467

Submitted: September 14, 2011 Accepted: October 15, 2011 Published: March 01, 2012

Power Quality Investigation in a Wind Power Generation System

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Abstract: Realizing the growing importance of wind energy, manufacturers have steadily been increasing the unit size of the wind electric generators since the late 1980s. The connection of large wind farms to the grid may cause problems in terms of power quality due to the variability of the energy extracted from the wind. The mentioned power quality problems are generally taken into consideration after the grid integration of wind farms. This paper discusses on the grid impedance evaluation method at wind farm terminals. The non-intrusive method uses variations of the wind power production, and this permanent variability allows us to apply the source impedance identification process, assuring its assessment. New algorithms are developed taking as a reference the accurate GPS synchronized measurement of phase at a very stable power plant, to evaluate the source impedance at a wind farm Point of Common Coupling (PCC) where complex variations of the voltage are expected. The instantaneous value of the grid impedance will, not only, allow assigning responsibilities but also will facilitate the design of equipments, network components, control systems tuning and protections configuration. The development of dispersed generation will be positively influenced by the capacity of measuring the network strength.

Key words: Grid impedance, power quality evaluation, wind power

INTRODUCTION

Standards are ready (Pfajfar *et al*., 2008) providing recommendations for preparing the measurements and assessment of power quality characteristics of wind turbines. One important question is raised: Are these fluctuations caused by the wind turbine or by other fluctuating loads? In other words, who is responsible? Generally, the influence of a wind turbine on the voltage quality of the grid depends not only on the turbine but also on the grid where it is connected. The European Wind Turbine Testing Procedure (EWTTP), (Sorensen, 2001) report has illustrated that the grid impedance angle and short circuit power have an important influence on power quality. We are then facing a very complex problem: how to assess the emission level of a particular distorted generation taking into account the instantaneous fundamental and harmonic source impedance variations of a power network.

Proposed measurement procedures are valid to test the power quality characteristic parameters for the full operational range of a wind turbine, connected to a MV or HV network with fixed frequency within ±1Hz, sufficient active and reactive power regulations capabilities and sufficient load to absorb the wind power production. The measurements procedures are designed to be as non-site-specific as possible, so that power quality characteristics measured at for example a test site can be considered valid also at other sites. The standard specifies a method that uses current $i_m(t)$ and voltage-time series $u_m(t)$ measured at the wind turbine terminals distributed over the wind speed interval from cut-in to 15 m/s, to simulate the voltage fluctuations on a “fictitious” grid with no source of voltage fluctuations other than the wind turbine. This fictitious grid is presented in the Fig. 1.

The fictitious grid is represented by an ideal phase to neutral rated voltage source $u_0(t)$ with an appropriate short-circuit apparent power $S_{k,fic}$, and four grid impedance angles ψ_k while the wind turbine is represented by a current generator $i_m(t)$, which is the measured instantaneous value of the phase current. Thus, the fluctuating voltage that will be input to the voltage flicker algorithm in compliance with IEC-61000-4-15 to generate the flicker emission value $P_{st,fic}$ is given as:

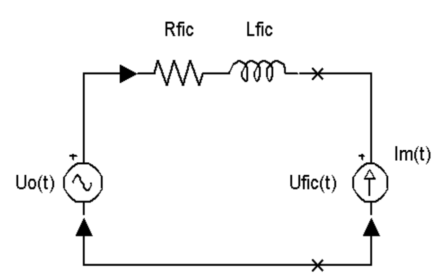

Fig. 1: Fictitious grid as proposed by IEC – 61400-21

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$$u_{fic}(t) = u_0(t) + R_{fic}.i_m(t) + L_{fic}.\frac{d}{dt}i_m(t) \quad (1)$$

The fundamental voltage has to be determined from measured voltage at the wind turbine terminals. If voltages and currents are sampled with a constant sampling frequency, the fundamental can be found by filtering the measured voltage and determining the zero crossings of the filtered signal, taking into account phase compensation due to filtering lag.

Once this measurement and simulation procedure is done, flicker coefficients $c(\psi_k, v_a)$ are then reported for continuous operation after normalization and weighting processes depending on the network impedance phase angle ψ_k and the annual average wind speed v_a values. Flicker step factors $k_f(\psi_k)$ and voltage change factors $k_U(\psi k)$ are generated together in the case of switching operations. These factors are normally measured and provided by manufacturers, who trend to overestimate them in some occasions as reported in (Chen and Spooner, 2001).

It is not the aim of this study to discuss the current methodology in use for coefficients estimation during the measurement procedure proposed by the standard, but to propose an improvement regarding the second phase of power quality assessment once the wind turbine is connected at the PCC. In order to evaluate the power quality expected from a wind turbine when deployed at a specific site, the following equation applies at continuous operation:

$$P_{st} = P_{lt} = c(\psi_k, v_c).\frac{S_n}{S_k} \quad (2)$$

where, S_n is the rated apparent power of the wind turbine and S_k is the short-circuit apparent power at the PCC. Other equations are applied to assess emissions from the sum of several wind turbines, and a similar procedure is proposed to estimate power quality during switching operations (Pfajfar *et al*., 2008).

Grid angle dependability is considered by selecting the right coefficient from manufacturer's data. Generally, the short-circuit apparent power is assessed by calculation. The nature and the accuracy of data to be provided for modeling the network are not always evaluated in the same way by the experts in charge of harmonics studies. Besides, the source impedance is a time-dependent parameter, varying with a changing network topology, as for example the connection or disconnection of a second parallel transmission line or a second transformer at the bus bar. The development of dispersed generation will lead to important short-circuit level variations as well. We propose to consider short-circuit apparent power variations of the real grid by evaluating both the fundamental and harmonic source impedance value and its angle. This possibility gives rise to new challenges on the voltage fluctuations assessment, such as more accurate grid-dependent on-line estimation of flicker emission levels. The influence of other fluctuating generators or loads that may cause significant voltage variations at the wind turbine terminals could be identified and responsibilities assigned.

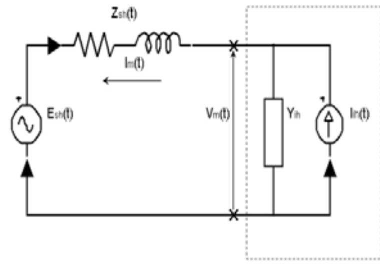

Fig. 2: Fundamental and harmonic single phase equivalent

Source impedance assessment process and proposed improvements: Our department has been working in the basis of Yang's method as one of the best ways to measure the fundamental and harmonic source impedance. More details about the process and its practical implementation can be found at (Xiaoqing *et al*., 2010). Considering a Thevenin equivalent network, a measured current change from I_{m1} to I_{m2} between instants t_1 and t_2, with their consequent voltage change from V_{m1} to V_{m2} will allow us to determine the true source impedance value. The voltage source E_{sh} value between windows is supposed invariable as well as the source impedance value Z_{sh}. The method is described in the next equations with a load approach:

$$\underline{V}_{m1} = \underline{E}_{sh} - \underline{Z}_{sh}\underline{I}_{m1} \quad (3)$$

$$\underline{V}_{m2} = \underline{E}_{sk} - \underline{Z}_{sk}\underline{I}_{m2} \quad (4)$$

$$\underline{Z}_{sh} = -\frac{\underline{\Delta V}}{\underline{\Delta I}} = -\frac{V_{m2}.e^{J\varphi_{vm2}} - V_{m1}.e^{J\varphi_{vm1}}}{I_{m2}.e^{J\varphi_{Im2}} - I_{m1}.e^{J\varphi_{Im1}}} \quad (5)$$

Considering the Fig. 2, if the true instantaneous Z_{sh} (fundamental and harmonic) value is known, then the normalized value $|Z_{sh}I_m|/|E_{sh}|$ represents physically the true harmonic emission level of an equivalent generation or load.

The harmonic voltage emission of the network itself, E_{sh}, can be determined easily from the measured voltage if the harmonic source impedance is known.

Some critical points have been encountered during the implementation phase, and solutions are proposed and evaluated to overcome them (Fig. 3).

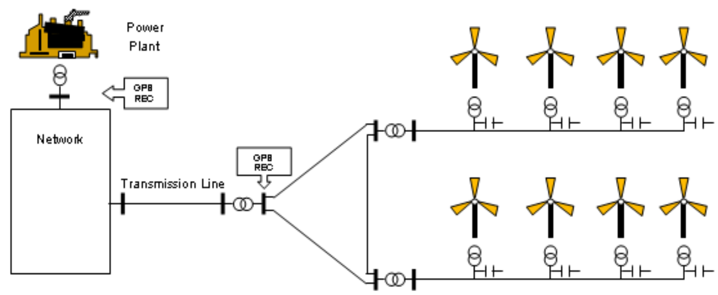

Fig. 3: Synchronized measurements at the power plant and the wind farm

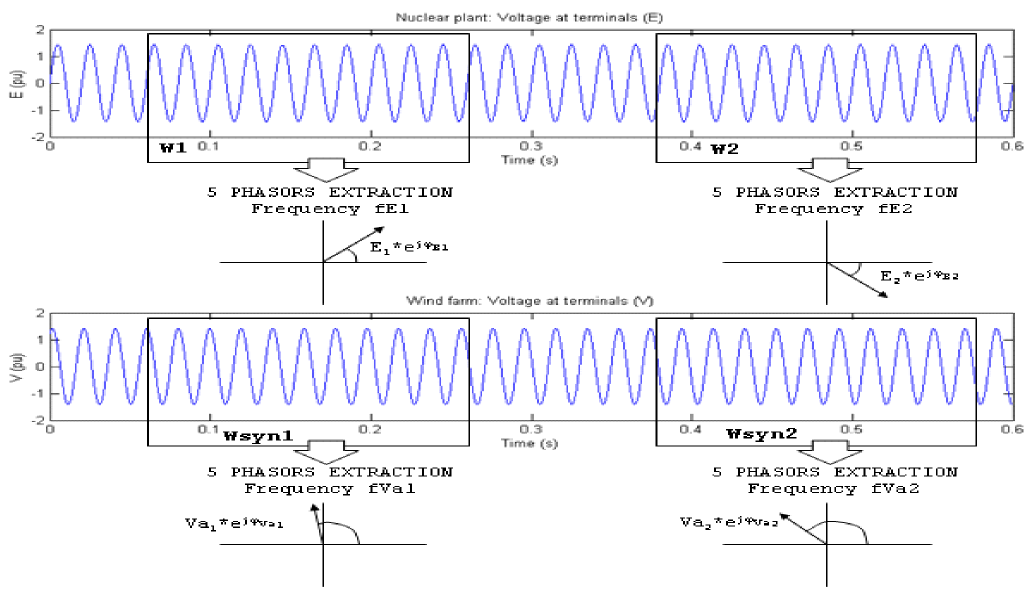

Fig. 4: Phasors extraction at a nuclear and wind farm

Accurate phasors calculation: Nowadays, the way to a chieve the extraction of fundamental frequency is by means of Phase Lock Loop (PLL) equipment. Sampling frequency is calculated with a delay of 400 ms (20 cycles). The phase shift between windows due to this FFT error may be corrected and compensated. But the system frequency variations remain an important source of errors when trying to be detected by the present technology in use and this is translated in bad phasors calculation. Accurate frequency tracking in a software basis algorithm (Conroy and Watson, 2007) is one of the new improvements to the process. In this way, 5 or 10 phasors are obtained per (200±t) ms window, with t the variable window length depending on the detected frequency, what allows more accurate phasors calculation between windows when determining Z_{sh}.

Slow current variations: The method was originally implemented with a delay of 400 ms between windows, not “slow” enough to reflect the overall modification of an event (2s). A continuous current monitoring system is proposed. Some work has been done based on a new algorithm for “current tracking” with the objective of detecting these slow variations and setting minimal thresholds between windows, taking into account the elapsed time between them to prevent any variation on source side (e_{sh} and $\underline{Z}_{sh}$).

Synchronization between windows: The process implicates another serious synchronization problem, when supposing the two states for Z_{sh} extraction placed at the same referential related to the system frequency at the time considered. Or in other words, the second measurement window shows a phase displacement of the voltage source E_{sh}. If basic hypothesis are maintained, the referential should remain invariable between windows. A synchronization in measurements taken at the terminals of a stable power plant (a nuclear unit for example) and at the wind farm terminals by GPS, is studied in this study. Two GPS receivers are installed at the nuclear power plant, considered as a reference and at the PCC where the wind farm is connected, as shown in Fig. 4.

The proposed synchronization algorithm is represented in Fig. 4. Obtained results of simulated voltage at the infinite bus (nuclear plant E) and at the wind farm terminals (V) time series are represented.

As it is seen from the Fig. 4, Window 1 (W1) at the nuclear power plant is synchronized with Window 1 (Wsyn1) at the wind farm terminals as for Window 2. Frequency is detected on a 10-cycle basis and phasors are calculated on a 2-cycle basis, obtaining 5 voltage phasors per window. Current time series are inputs to the algorithm at the same time and phasors are extracted at the wind farm terminals. Currents are not represented in the Fig. 4. Voltage phasors are computed at the frequency of the nuclear plant, V_{a1} is computed at f_{E1} and V_{a2} is computed at f_{E2} even if the values of fV_{a1} and fV_{a2} frequencies are also calculated and known. Frequency at the wind farm terminals is fluctuating around 50Hz during all the simulation period.

Several tests have been performed correcting measured voltage phase at the wind farm terminals. Using the same:

$$Z_s = -\frac{\Delta V}{\Delta I} = -\frac{Va_2 .e^{j\varphi Va_2} .e^{-j\varphi E_2} - Va_1 .e^{j\varphi Va_1} .e^{-j\varphi E_1}}{Ia_2 .e^{j\varphi Ia_2} .e^{-j\varphi E_2} - Ia_1 .e^{j\varphi Ia_1} .e^{-j\varphi E_1}} \quad (6)$$

The method has been tested on a simplified network and final algorithms have been applied to several simulated wind power schemes. Results are presented in this paper. Using the accurate timing signal provided by Global Positioning system (GPS satellite Universal Coordinated Time (UTC)) as common time base for measuring instruments located at both sites we can highly promote the accuracy of synchronized measurements. There are two required outputs of these devices and several optional outputs. The first is a precise digital output with 50 ns rise time that occurs once per second transition of UCT. The second is an ASCII message that identifies the year, day, hour, minute and second of the digital output. Manufacturers are flexible in providing other outputs requested for specialized uses. Because of low frequency of the timing signal of GPS, it can not be used as sampling signal directly. Several options can be adopted for communications like telephone lines, fibre-optic cables, satellites, power lines or microwave links. The synchronization will be achieved locally, at the wind farm terminals by matching the time-stamps of measurements obtained from both sites by a posterior signal analysis. These implementation matters as well as problems related from the communication delays are out of the scope of this study.

Wind turbine simulation results: One wind turbine unit of 2 MW rated power belonging to the BONUS family with a fixed battery of 600 kVAr for reactive compensation is connected to an equivalent Thevenin source composed by a voltage source 690V and inductive source impedance. The source impedance in per unit is $0.125\angle 90°$ in a 2MVA-690V basis. Several tests have been conducted allowing a wide variation of different simulation parameters**.**

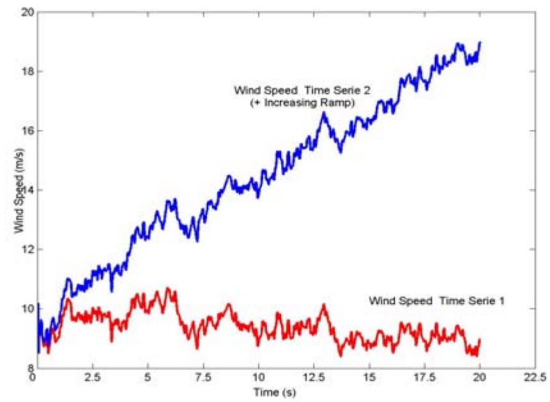

Fig. 5: Wind speed series, ramp variation as an input to the simulation

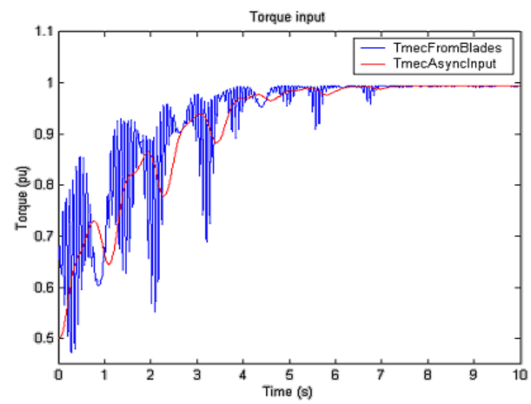

Fig. 6: Mechanical torque from blades and input torque to the asynchronous generator

Wind speed variations: Wind speed as an input to the simulations has been modeled either as a ramp increasing from 10 m/s with a wind acceleration of $1 m/s^2$ or as a step change from 10 to 12 m/s, both speeds having a constant value during at least 5 s, having in mind an increasing relatively slowly wind or a sudden step change. More complex simulations have been performed taking as an input a wind speed time series generated from the Kaimal spectra (Conroy and Watson, 2007). This wind series is generated around a mean speed value, and increased by a ramp, as it can be seen in Fig. 5.

Damping coefficients: Damping coefficients representing frictional torque at the slow speed shaft, gearbox and high speed shaft have been varied. The wind turbine low

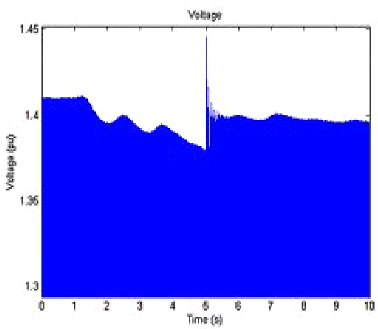

Fig. 7: Voltage at terminals (pu)

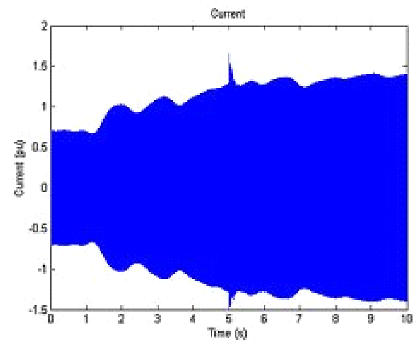

Fig. 8: Current at terminals (pu)

Table 1: Fundamental source impedance mean values

	Zs amplitude (pu)	Zs angle (Degrees)
Wind Ramp (10 m/s +Acc 1 m/s^2)		
Stability Threshold 5%	0.1248	89.7918
Stability Threshold 50%	0.1257	89.6640
Wind Step (10-12 m/s)		
Stability Threshold 5%	0.1257	89.5243
Stability Threshold 50%	0.1254	89.9597
Variable Wind + Increasing Ramp		
Stability Threshold 5%	0.1250	89.6859
Stability Threshold 50%	0.1251	89.9330

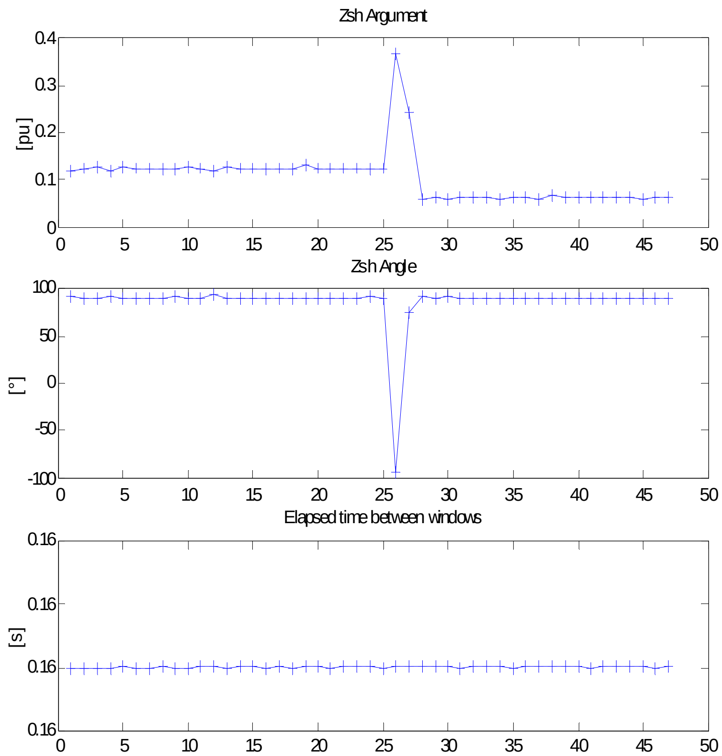

Fig. 9: Fundamental source impedance monitoring

frequency oscillations due to the blades mechanical interaction at higher wind speeds is strongly damped for higher coefficients, consequent harmonics are not always present at a wind farm measured current since the wind unit damps higher torsional frequencies. This is illustrated in the Fig. 6.

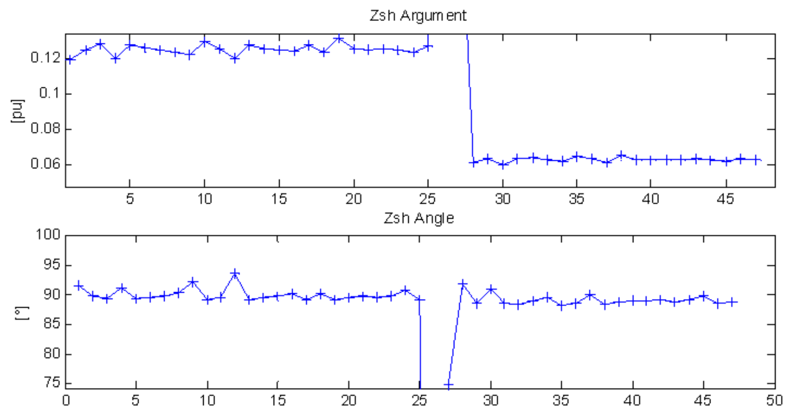

Fig. 10: Argument and phase detail

Zs algorithm stability: One new objective has been posed with regard to the in-window stability of the process since currents and voltages show important fluctuations within one calculation window. Possible solutions have been proposed to allow the Z_{sh} calculation between two measured windows, such as a minimal threshold of phasor variations. This precondition defines the algorithm sensibility and assures the minimum signal stability for a correct Zs detection. Simulated measurements of wind turbine current and voltage in phase A are performed at a sampling frequency of 20 kHz at the wind turbine terminals and resampled to an accurate fundamental phasors detection. Amplitude and phase of voltage and current phasors are then calculated, phase corrected and the Zs calculation is performed every two windows testing different threshold sensibility values.

Next Table 1 presents the fundamental source impedance mean values over 10 s (amplitude and angle) obtained from different simulations performed at a constant Z_{sh} value ($0.125\angle 90°$) varying stability thresholds. Accuracy increases with more severe stability criteria.

Source impedance variations: One of the simulations has been performed with the connection of a second equivalent voltage source in parallel, having equal short circuit power, what imposes a new source impedance value of $0.0625\angle 90°$. This is done to simulate the eventual variations of network topology, a parallel connection of a second transformer for example. Voltage and current instantaneous values taken as an input to the Zs algorithm are plotted in Fig. 7 and 8.

The source impedance step is done at t = 5s. This sudden variation causes a transient, detected by the algorithm as seen in Fig. 9, where the fundamental source impedance calculation is accurately performed and the magnitude and phase is plotted versus window calculation number. The third plot shows the elapsed time between calculation windows. This parameter is also monitored and limited in order to respect the basic hypothesis when applying the method. In this case, an assessment of Z_{sh} is performed every two windows of 160 ms length.

A more detailed Fig. 10 is presented. The mean Zs detected value before network switching is $0.1248\angle 89.1279$ pu and after network operation, $0.0625\angle 90.0213$ pu.

CONCLUSION

A wind farm simulation has been performed over a short period of time (10 s), long enough for our initial objectives, the evaluation of developed Zs algorithms with measurement synchronization to solve the frequency deviation problem during windows acquisition over time. A GPS synchronization to a nuclear power plant considered as our reference is proposed and evaluated. he “frequency tracking” resampling algorithm has been implemented to overcome the PLL inaccuracy and to improve phasor calculation. Signal stability within a measurement window remains the most important challenge to increase the robustness of the process.

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