STANDARDS FOR MEASUREMENTS AND TESTING OF WIND TURBINE POWER QUALITY

Poul Sørensen, Risø National Laboratory, P.O.Box 49, DK-4000 Roskilde, Denmark.
Gert Gerdes, Rainer Klosse and Fritz Santjer, DEWI, Ebertstrasse 96, D-26382 Wilhelmshaven, Germany.
Niel Robertson and Willie Davy, NEL, East Kilbride, UK-Glasgow G75 0QU, United Kingdom.
Maria Koulouvari and Evangelis Morfiadakis, CRES, 19th km Marathonos Ave., GR-19009 Pikermi, Greece.
Åke Larsson, Chalmers University of Technology, S-412 96 Göteborg, Sweden.

ABSTRACT: The present paper describes the work done in power quality subtask of the project ”European Wind Turbine Testing Procedure Developments” funded by the EU SMT program. The objective of the power quality subtask has been to make analyses and new recommendation(s) for the standardisation of measurement and verification of wind turbine power quality. The work has been organised in three major activities.

The first activity has been to propose measurement procedures and to verify existing and new measurement procedures. This activity has also involved a comparison of the measurements and data processing of the participating partners.

The second activity has been to investigate the influence of terrain, grid properties and wind farm summation on the power quality of wind turbines with constant rotor speed.

The third activity has been to investigate the influence of terrain, grid properties and wind farm summation on the power quality of wind turbines with variable rotor speed .

Kewords: Power Quality, Standards, Electrical System, Wind Farm.

1 INTRODUCTION

The increased size of standard grid connected wind turbines and the utilisation of wind turbines in larger scales has caused an increasing influence of wind turbines on voltage quality of the power system.

Methods to measure and quantify the power quality of wind turbines were early developed on national level, but the need for common reference across the boarders has initiated international standardisation work in the field.

The EU project ”European Wind Turbine Standards” (EWTS) [3] funded by the Joule II Programme defined an ”Electrical Power Quality Measurement Procedure” in February 1996, based mainly on the German standard. The EWTS procedure formed the basis for the Measnet measurement procedure on ”Power Quality of Wind Turbines”[2].

IEC initiated the standardisation on power quality for wind turbines in 1995 as a part of the wind turbine standardisation in TC88, and ultimo 1998 IEC issued a draft IEC-61400-21 standard for ”Power Quality Requirements for Grid Connected Wind Turbines”[1].

2 MEASUREMENT PROCEDURES

To verify the measurement procedures, all partners have measured power quality characteristics simultaneously on a 600 kW Bonus wind turbine in Hagshaw Hill wind farm in Scotland 13 - 17 October.

The power quality characteristics that were measured were reactive power, power variability, flicker, transients and harmonics. Both Measnet and IEC definitions have been applied.

2.1 Reactive power

The measured reactive power is shown vs. active power in Figure 1. Only data from a single hour is included, to avoid the influence of different voltage levels on the reactive power.

The figure reveals that Risø measures slightly lower values of consumed reactive power than DEWI and CRES. Analysis of the differences showed that the measurements were within the 2 % required in the Measnet procedure, and the requirements of the draft IEC61400-21.

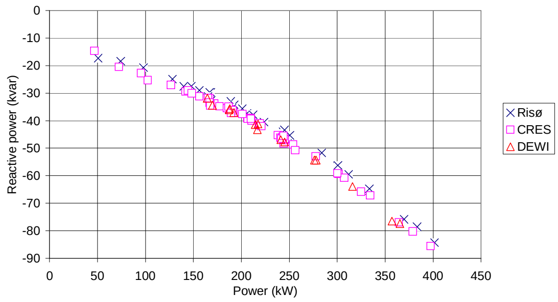

Figure 1. One minute mean values of reactive power vs. active power measured in the same period by Risø, DEWI and CRES.

2.2 Power variability

IEC and Measnet prescribes measurement of maximum instantaneous values of power as a characteristic for the power variations. Besides, a power variability is defined in the Measnet procedure as the relative standard deviation of the power.

The measured standard deviations of the power have shown to be very close. The maximum values show more deviations in the results. One reason for this has been the sampling rate. In Hagshaw Hill, CRES measured power with 20-25 samples per minute, which showed to be too little to measure the power peaks, because some of the power fluctuations are much faster.

2.3 Flicker simulation procedure

Flicker is defined in IEC 868 [4] and [5] to quantify the annoyance in the illumination from lamps. This annoyance depends on the voltage fluctuations at the consumers.

The voltage fluctuations at the consumers depend on fluctuating loads as well as fluctuating production in the power system. The power from wind turbines is fluctuating, and therefore the wind turbines contribute to the voltage fluctuations on the grid.

IEC 1000-3-7 [6] states a method to plan the voltage flicker level in the MV and HV level of a power system, based on the emission level of the individual loads on the system. The emission level of a fluctuating load is defined as the flicker level, which would be produced in the power system if no other fluctuating loads were present.

Measurements of power quality are done on real grids with other fluctuating loads. To eliminate the influence of the fluctuations of the other loads, a method has been developed to simulate the voltage, which would be on a power system with no other fluctuating loads.

The voltage is simulated as $u_{fic}(t)$ on the fictitious reference grid seen in Figure 2.

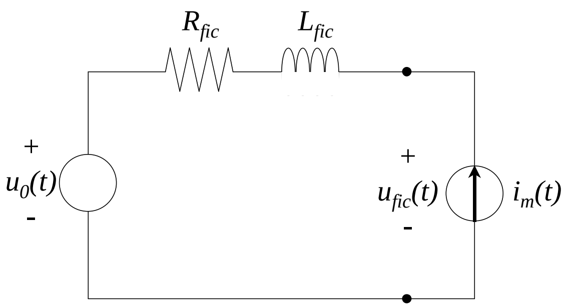

Figure 2. Simulation of voltage which would be on a power system with no other fluctuating loads.

The fictitious grid is represented by an ideal phase to neutral voltage source $u_0(t)$ and a grid impedance given as a resistance R_{fic} in series with an inductance L_{fic}. The wind turbine is represented by the current generator $i_m(t)$, which is the measured instantaneous value of the phase current.

With this simple model, the fluctuating voltage $u_{fic}(t)$ in the power system is given as

$$u_{fic}(t) = u_0(t) + R_{fic} \cdot i_m(t) + L_{fic} \cdot \frac{di_m(t)}{dt}$$

$u_{fic}(t)$ is then used as input to a voltage flicker algorithm as described in IEC 868.

2.4 Flicker during continuous operation

Table 1 shows measurements of flicker short term values with continuous operation of the Bonus 600 kW wind turbine in Hagshaw Hill. The measurements were synchronised manually, i.e. within 1-2 seconds.

Table 1. Simultaneously measured flicker Pst with short circuit ratio 20, grid impedance angles Ψ_k

Me. #	Ψ_k	CRES	DEWI	NEL	Risø
1	30	0.185	0.184	0.169	0.191
2	50	0.121	0.129	0.116	0.138
3	70	-	0.042	-	0..053
	85	-	0.025	-	0.041
4	70	0.074	0.060	0.074	-

Risø used active and reactive power measurements to predict the flicker level with a power based method described in [9], CRES and NEL used a Voltech power analyser with built in current flicker software, and DEWI used own software to simulate the flicker.

This and other results show that flickermeters have a minimum Pst value due to the the binning of the instantaneous flicker level in classes. The Voltech power analyser have a minimum Pst value of 0.074, even though it uses a more detailed binning than required in IEC 868.

Consequently, a weak reference grid (i.e. low short circuit power) shall be selected for the reference calculations. If a too strong grid is selected then the calculated flicker value will be the minimum value of the instrument. Using this Pst value to estimate Pst on weaker grids will only give a scaled minimum value.

2.5 Transients during switching

Wind turbines typically generate transient currents during cut-in and cut-out and switching between generators.

In the EWTS procedure, the transients were characterised by current spike factors, i.e. the ratio between the maximum RMS value of the current and the rated current.

In the Measnet procedure, the current spike factor was supplemented with a grid dependent switching factor, which can be used to predict the maximum voltage variation, taking into account the grid impedance angle.

The definitions in the draft IEC 61400-21 aim to specify characteristics, which can be used to assess the voltage fluctuations according to IEC 1000-3-7 [6]. Consequently, the IEC draft has omitted the current spike factor, but defines a voltage change factor almost similar to Measnets grid dependent switching factor. Moreover, the draft IEC 61400-21 defines a flicker step factor which can be used to predict the flicker influence of the switching operation.

A set of reference measurements logged by DEWI in Hagshaw Hill have been used to compare the calculation routines for flicker. The results of the calculated flicker step factors for the cut-in operation are shown in Figure 3.

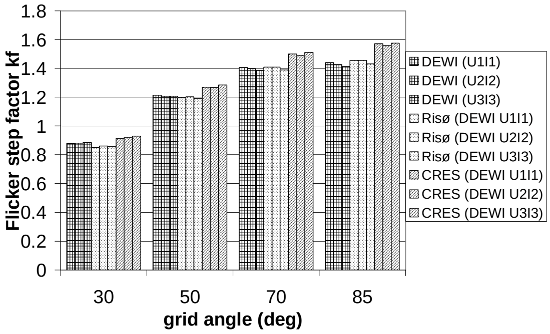

Figure 3. Comparison of calculated flicker step factors k_f during cut-in.

2.6 Harmonics

The harmonic measurements in Hagshaw Hill have also been compared. Generally, the harmonic emission was very low, because the wind turbines are not equipped with power electronics for power conversion. However, the comparisons have shown that the measurements and calculation software of the partners predict harmonics within the 0.1 pct. of rated current which is required in the draft IEC 61400-21.

3 CONSTANT SPEED WIND TURBINES.

The power quality measurements in Hagshaw Hill have been compared to measurements on the same type of 600 kW Bonus wind turbine in Gudum in Denmark. The wind turbine is stall regulated with one rotor speed.

The main difference between the two sites is the terrain. The Hagshaw Hill wind farm is sited in complex terrain, whereas the Gudum wind turbines are sited in a more flat terrain. Another difference appeared to be that the voltage level in Hagshaw Hill is higher than in Gudum.

3.1 Reactive power

Figure 4 shows 10 min mean values of the reactive power vs active power measured by Risø with the same power transducers in Hagshaw Hill and Gudum.

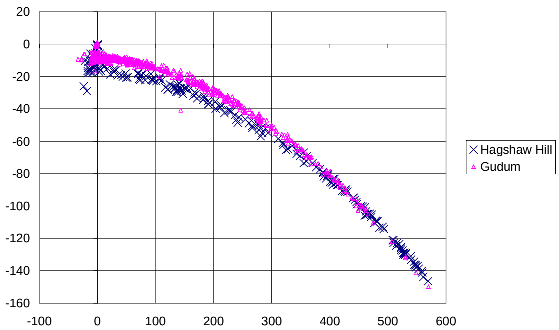

Figure 4. The reactive power consumption of the Bonus 600 kW wind turbine in Hagshaw Hill (Scotland) and Gudum (Denmark)

The analysis showed that the deviations in reactive power are due to a combination of different effects. First, the difference in reactive power consumption at low power levels is most likely due to deviations in the capacities in the capacitor banks. Secondly, the reactive power consumption increases more with power in Gudum than in Hagshaw Hill, which is implied by the higher voltage level in Hagshaw Hill. The lower voltage in Gudum gives higher currents, which again implies higher reactive power consumption in the leak inductance of the induction generator.

3.2 Flicker during continuous operation

The flicker level is effected by the terrain as illustrated in Figure 5. Generally, the Pst values are higher in Hagshaw Hill than in Gudum. This is as expected because of the complex terrain in Hagshaw Hill. But it is also seen that the flicker values increase faster with power in Gudum than in Hagshaw Hill. This is a very important point, because the requirements on flicker emission are based on 99% percentile values. Figure 5 indicates that even though the flicker level is 100% higher in Hagshaw Hill in the medium power range, the 99 % percentiles will only be approximately 20 % higher in Hagshaw Hill than in Gudum.

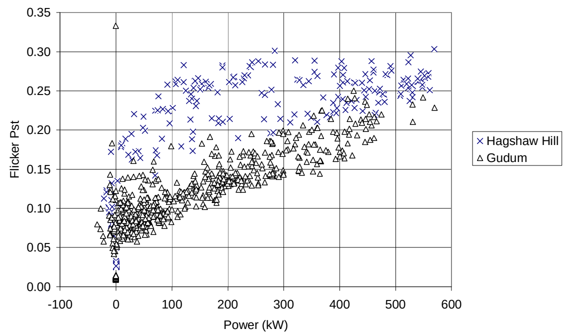

Figure 5. Flicker Pst values vs. power of Bonus 600 kW wind turbines in Hagshaw Hill (complex terrain) and Gudum (flat terrain) for grid angle 30 deg.

3.3 Transients during switching

The higher voltage level in Hagshaw Hill also effects the flicker emission during cut-ins of the wind turbine, and consequently the flicker step factor. The higher voltage level implies more reactive power to magnetise the induction generator at cut-in. This transient reactive power for magnetising has a decisive influence on the flicker emission during cut-in.

3.4 Summation of flicker

According to IEC 1000-3-7 [6], the combined flicker emission P_{st} from various loads can be found as

$$P_{st} = \sqrt[m]{\sum_i P_{st,i}{}^m}$$

where $P_{st,i}$ is the flicker emission from the ith load, and m is an exponent depending on the type of the loads. Analyses have shown that for continuous operation of wind turbines, m=2 gives excellent results. For switching operations, m=3.2 is recommended because this value fits when the switching operations do not coincide.

3.5 Harmonics

The harmonic measurements in Hagshaw Hill have also been compared. Generally, the harmonic emission was very low, because the wind turbines are not equipped with power electronics for power conversion. However, the comparisons have shown that the measurements and calculation software of the partners predict harmonics within the 0.1 pct. of rated current which is required in the draft IEC 61400-21.

4 VARIABLE SPEED WIND TURBINES.

The analyses of power quality of variable speed wind turbines are based on measurements on Enercon E-40 wind turbines with power converters based on forced-commutated semiconductors.

4.1 Reactive power

The use of forced-commutated semiconductors makes it possible to control the power factor. Figure 6 shows the measured reactive power as a function of the active power from two different sites. The averaging time in the measurements are in both cases 1 minute. At Gotland the power factor is approximately 0,98 and at Skåne 0,99.

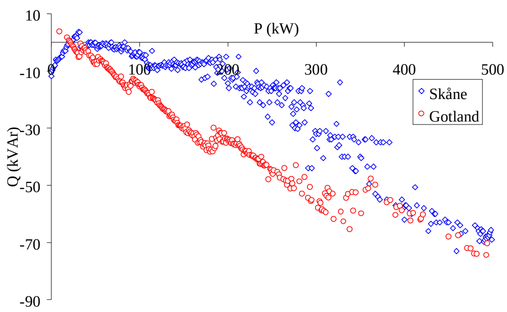

Figure 6. Reactive power as a function of active power from two different sites, Gotland and Skåne.

4.2 Transients during switching

With a combined variable speed control and pitch control of the Enercon wind turbine, the cut-ins and cut-outs can be controlled to a very low level of flicker emission.

4.3 Harmonics and interharmonics

The use of power converters implies a higher emission of harmonics and interharmonics on the grid. The traditional self-commutated semiconcuctors, i.e. thyristors, mainly emit harmonics at low orders. Modern power converters based on forced-commutated semiconductors like IGBTs can be controlled to switch at much higher frequencies. Besides, the emission is not concentrated on harmonics of the fundamental grid frequency, but distributed between the harmonics as interharmonics.

IEC has initiated a revision of 61000-4-7[7] in order to improve the measurement methods for interharmonics. The draft IEC 61400-21 keeps measurements of interharmonic under consideration, awaiting this revision. Meanwhile, Measnet will specify a method based on a CD of the revision [8].

5 CONCLUSIONS

The results from comparisons of simultaneous measurements in Hagshaw Hill show good agreement between the measurements of Risø, DEWI, NEL and CRES. Moreover, the comparison of calculation results based on a set of reference measurements showed very good agreement between the analysis software of Risø, DEWI and CRES.

Measnet and IEC define methods to measure power quality characteristics, which aim at being independent on the grid where the measurements are done. The measured power quality characteristics can then be applied to calculate the influence on the voltage quality on another grid, characterised by a short circuit power and an impedance angle.

The present work has illustrated that the grid properties still have an influence on the specified power quality characteristics.

Another factor, which influences the results, is the terrain. The comparison between measurements in complex terrain and in relatively flat terrain showed significant difference between the measurements of power variability and flicker at low and medium wind speed, but the designing 99% percentiles were less sensitive to the terrain.

All these effects could be taken into account by advanced methods, but such methods would depend strongly on the technology. The strength of the existing methods is their simplicity combined with a high degree of independence of technology. Even the specified methods do have limits concerning the technology. For instance, the specified method to measure flicker emission is not relevant to characterise a wind turbine with a voltage controlling power converter.

REFERENCES

[1] International Electrotechnical Commission. Draft IEC 61400-21: Power Quality Requirements for Grid Connected Wind Turbines. Committee Draft (CD) 1998-12-11.

[2] Measnet Measurement Procedure. Power Quality of Wind Turbines. Draft 27.11.96.

[3] European Wind Turbine Standards. Volume 7. Electrical Power Quality Measurement Procedure. Final Draft February 1996.

[4] International Electrotechnical Commission. IEC Report. Publication 868. Flickermeter. Functional and design specifications. First edition 1986.

[5] International Electrotechnical Commission. Amendment 1 to Publication 868 (1986). Flickermeter. Functional and design specifications. 1990-07.

[6] International Electrotechnical Commission. Technical Report 1000-3-7. Electromagnetic compatibility (EMC) – Part 3: Limits – Section 7: Assessment of

emission limits for fluctuating loads on MV and HV power systems – Basic EMC publication. First edition 1996.
[7] International Electrotechnical Commission. IEC 61000-4-7. Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 7: General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto. First Edition 1991-07.
[8] International Electrotechnical Commission. Revision of 61000-4-7. Electromagnetic compatibility (EMC) – Part 4: Testing and measurement techniques – Section 7: General guide on harmonics and interharmonics measurements and instrumentation, for power supply systems and equipment connected thereto. Committee draft 1997-12-15.
[9] P. Sørensen. Methods for calculation of the flicker contributions from wind turbines. Risø-I-939(EN). December 1995.