POWER QUALITY MEASUREMENT PROCEDURE

Version 4
October 2009

List of Contents

1. Foreword

MEASNET is a network of measurement institutes which have been established to harmonise wind energy related measurement procedures. The institutes of MEASNET are all actively performing wind energy related measurements. Each institute has to document the skills and quality of measurements, to apply agreed “MEASNET measurement procedures” and to participate as required in mutual evaluation exercises.

2. Introduction

The MEASNET Power Quality Measurement Procedure is the measurement procedure agreed upon by the MEASNET members to be mutually used and accepted. The procedure is considered to be the most internationally accepted procedure on which a common interpretation and understanding has been exercised in accordance with the MEASNET Quality Evaluation Program, based on the objective of continuously improving quality in measurements.

3. The reference measurement procedure

The measurement procedure is based on the IEC 61400-21 [1].

4. Additional requirements

Further additional requirements to the reference procedure are given in order to strengthen the quality and inter-comparability of the measurements.

With reference to the chapter numbers of IEC 61400-21, the additional Measnet requirements are:

4.1 Rated Data (IEC section 7.2)

The rated active power P_n, the rated reactive power Q_n, the rated apparent power S_n, the rated voltage U_n and the rated current I_n are based on manufacturer’s information, but not necessarily on measurements. Thus the measured current and reactive and apparent power at rated active power can possibly deviate from the rated values.

4.2 Flicker in continuous operation (IEC section 7.3.3)

For the flicker measurement wind speed bins of 1 m/s are used starting from integer values up to <15 m/s. In case cut-in wind speed is not an integer value then it is rounded down to the closest integer (example: in case the cut-in wind speed is 3.5 m/s, then the first wind speed bin is from 3 m/s up to < 4 m/s).

4.3 Analysis of voltages, currents, active and reactive power

For the calculation of active and reactive power, active and reactive current and voltage it is required to follow the method of the positive sequence calculation, given in Annex C of the IEC 61400-21 [1].

4.4 Response to temporary voltage drops (IEC chapter 6.5)

The reference guideline (IEC 61400-21) gives voltage dip tests in Table 1 of section 6.5. Grid operators often require different voltage dip tests. It is in accordance with this MEASNET guideline to perform voltage dip tests with different times and voltage depths than given in the IEC guideline.

4.5 Uncertainty Analysis

It is required that an **uncertainty analysis** is carried out in accordance with the ISO guide to the expression of uncertainty [2] . The procedure for estimating the uncertainty of the power quality measurements is described in Appendix B.

5. Bibliography

[1] IEC 61400-21 Ed. 2 (2008-8): Wind Turbines, Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines.

[2] ISO/IEC Guide 98-3:2008(E) Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

[3] IEC 61400-12-1 – Power performance measurements of electricity producing wind turbines, First edition

Annex A: Data Sheet

DATA SHEET OF POWER QUALITY MEASUREMENT

According to Measnet Power Quality Procedure, Version 4

Report:		Sheet:		page 1 of 22
Wind turbine type designation:		Serial number:		
Wind turbine manufacturer:				

Description of the tested wind turbine, including settings of control parameters:	Document name and date
Description of the test site and grid connection:	
Description of the test equipment:	
Description of test conditions:	

Name and address of test organisation:			
Author:		Checked:	
Date of issue:		Approved:	

Note of exceptions to Measnet Power Quality Procedure:

General data:

Number of blades:		Generator type and rating: [kW]	
Rotor diameter [m]:			
Hub height [m]:		Grid side converter type and rating [kVA]	
Blade control (pitch/stall):			
Cut-in wind speed [m/s]		Special features:	
Speed control (fixed/2speed/variable):			
Speed range [rpm]			
Wind turbine type (doubly fed / full converter / direct coupled / others)			

Rated data:

Rated power, P_n:[kW]		Rated apparent power, S_n: [kVA]	
Rated wind speed, v_n:[m/s]		Rated current, I_n: [A]	
Rated voltage, U_n: [V]		Rated frequency, f_n [Hz]	

DATA SHEET OF POWER QUALITY MEASUREMENT

According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 2 of 22

Maximum measured power:

Max. measured 600 sec. average		Max. measured 60 sec. average		Max. measured 0.2 sec. average	
P_{600}	$p_{600}=P_{600}/P_n$	P_{60}	$p_{60}=P_{60}/P_n$	$P_{0.2}$	$p_{0.2}=P_{0.2}/P_n$

Reactive power:

Output power bin P/P_n		Output power bin-mean-value [kW]	Reactive power bin-mean-value [kvar]
from -0.05	to <0.05		
0.05	<0.15		
0.15	<0.25		
0.25	<0.35		
0.35	<0.45		
0.45	<0.55		
0.55	<0.65		
0.65	<0.75		
0.75	<0.85		
0.85	<0.95		
0.95	<1.05		
Operational mode (reactive set point control Q=0 / others)			

Flicker:

Network impedance phase angle, ψ_k:	30°	50°	70°	85°
Annual average wind speed, v_a(m/s):	Flicker coefficient, $c(\psi_k,v_a)$:			
6.0 m/s				
7.5 m/s				
8.5 m/s				
10 m/s				
Operational mode (reactive set point control Q=0 / others)				

DATA SHEET OF POWER QUALITY MEASUREMENT

According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 3 of 22

Switching operations:

Operational mode for switchings (reactive set point control Q=0 / others)	

Case of switching operation:	Start-up at cut in wind speed			
Maximum number of switching operations, N_{10m}:				
Maximum number of switching operations, N_{120m}:				
Network impedance phase angle, ψ_k:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:				
Voltage change factor, $k_U(\psi_k)$:				

Case of switching operation:	Start-up at rated wind speed or higher			
Maximum number of switching operations, N_{10m}:				
Maximum number of switching operations, N_{120m}:				
Network impedance phase angle, ψ_k:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:				
Voltage change factor, $k_U(\psi_k)$:				

Case of switching operation:	Worst case switching between generators:			
Maximum number of switching operations, N_{10m}:				
Maximum number of switching operations, N_{120m}:				
Network impedance phase angle, ψ_k:	**30°**	**50°**	**70°**	**85°**
Flicker step factor, $k_f(\psi_k)$:				
Voltage change factor, $k_U(\psi_k)$:				

DATA SHEET OF POWER QUALITY MEASUREMENT

According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 4 of 22

Operational mode during the test (reactive set point control Q=0 / others)	

Harmonics currents

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100
H	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)
2											
3											
4											
5											
6											
7											
8											
9											
10											
11											
12											
13											
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39											
40											
41											
42											
43											
44											
45											
46											
47											
48											
49											
50											
THC (%)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Wind turbine type:		Sheet:		page 5 of 22

Interharmonic currents

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100
f (Hz)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)
75/90											
125/150											
175/210											
225/270											
275/330											
325/390											
375/450											
425/510											
475/570											
525/630											
575/690											
625/750											
675/810											
725/870											
775/930											
825/990											
875/1050											
925/1110											
975/1170											
1025/1230											
1075/1290											
1125/1350											
1175/1410											
1225/1470											
1275/1530											
1325/1590											
1375/1650											
1425/1710											
1475/1770											
1525/1830											
1575/1890											
1625/1950											
1675											
1725											
1775											
1825											
1875											
1925											
1975											

DATA SHEET OF POWER QUALITY MEASUREMENT
According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 6 of 22

Higher frequency components

P_{bin} (%)	0	10	20	30	40	50	60	70	80	90	100
f (kHz)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)
2,1											
2,3											
2,5											
2,7											
2,9											
3,1											
3,3											
3,5											
3,7											
3,9											
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7,1											
7,3											
7,5											
7,7											
7,9											
8,1											
8,3											
8,5											
8,7											
8,9											

DATA SHEET OF POWER QUALITY MEASUREMENT

According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 7 of 22

Active power ramp rate limitation:

Operational mode of the wind turbine during the test (ramp rate limitation set to 10 % of rated power per minute / others)	

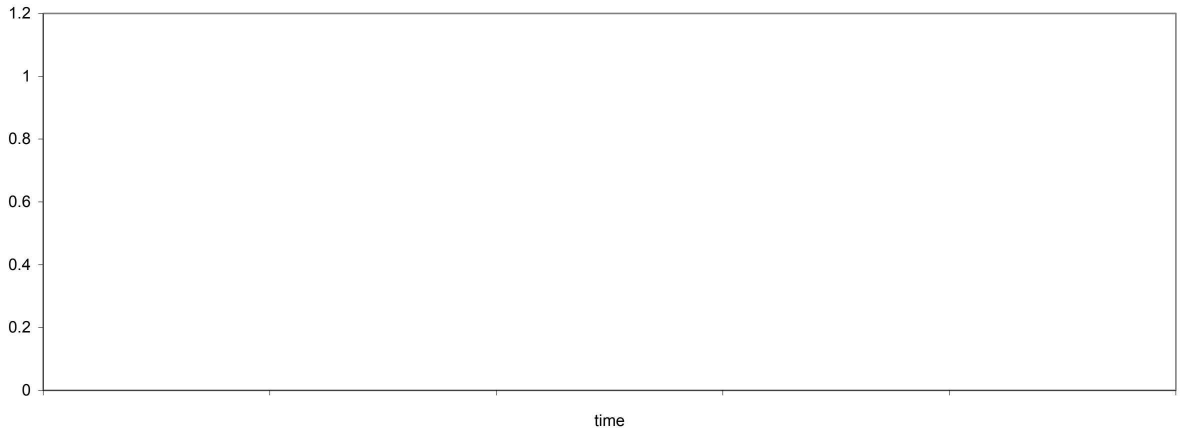

Figure: Time-series of available and measured active power output during ramp rate limitation

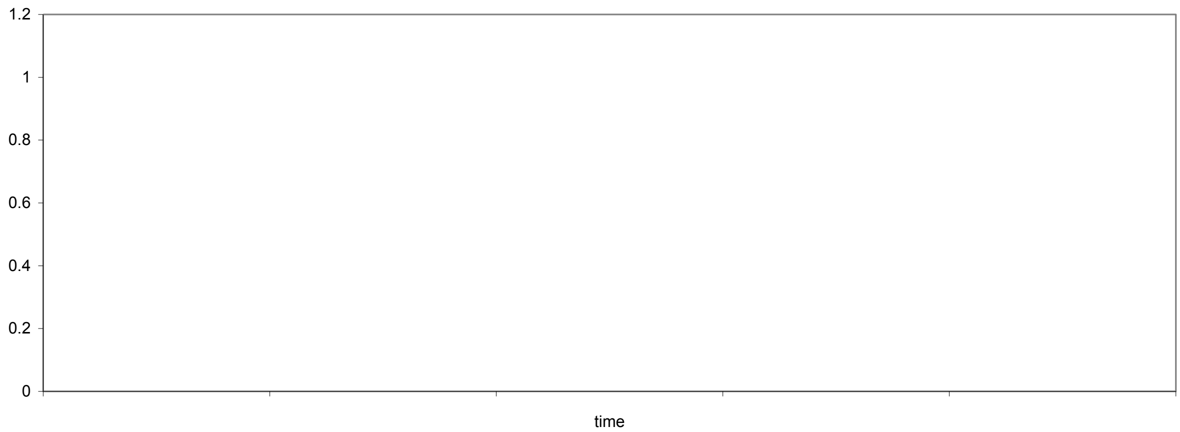

Figure: Time-series of measured wind speed during ramp rate limitation

DATA SHEET OF POWER QUALITY MEASUREMENT
According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 8 of 22

Active power set-point control:

Operational mode of the wind turbine during the test (active power set-point control mode / others)	

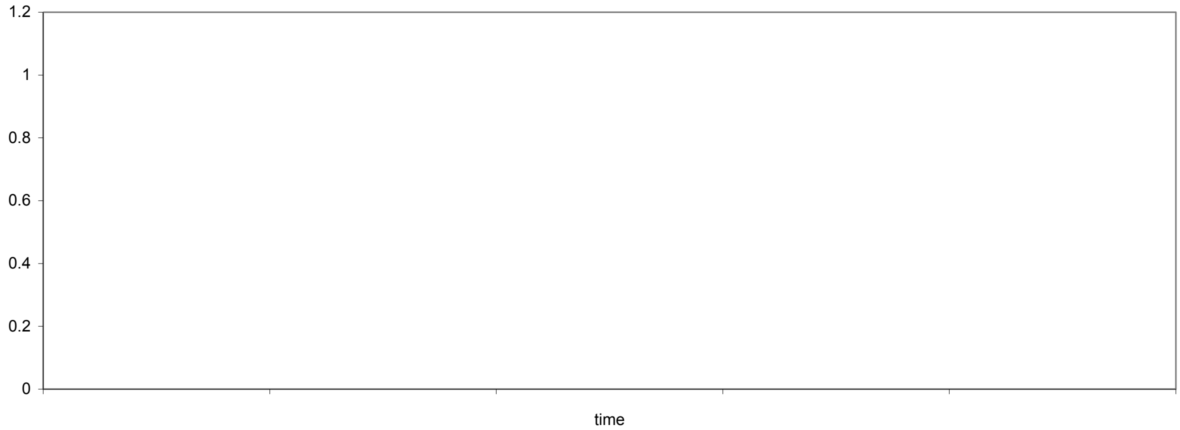

Figure: Time-series of active power set-point values, available power and measured active power output during active power set point control

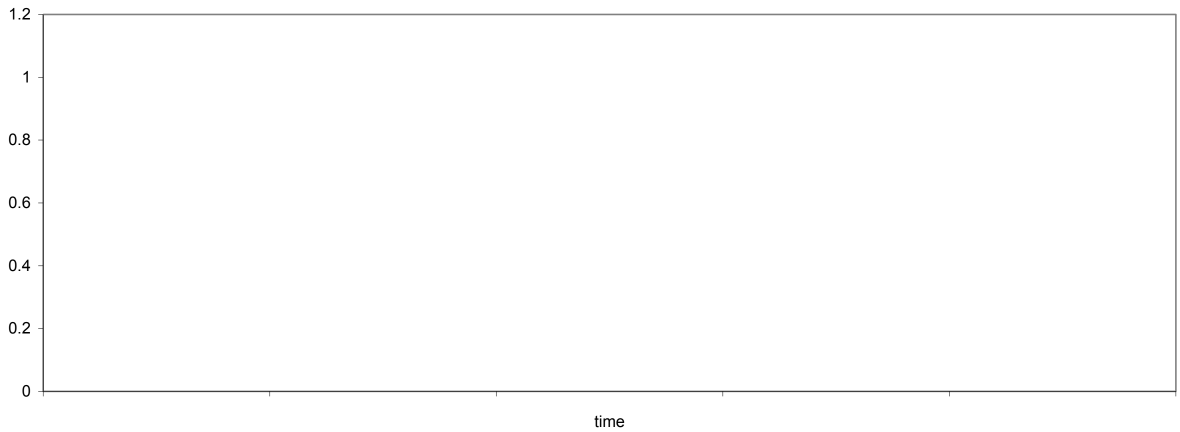

Figure: Time-series of measured wind speed during active power set point control

DATA SHEET OF POWER QUALITY MEASUREMENT
According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 9 of 22

Reactive power capability:

Active power P_{bin} [%]	*0*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
Max. inductive reactive power [kvar]											
Max. capacitive reactive power [kvar]											
Operational mode of the wind turbine during the test (active power set-point control mode / others)											

Reactive power set point step change:

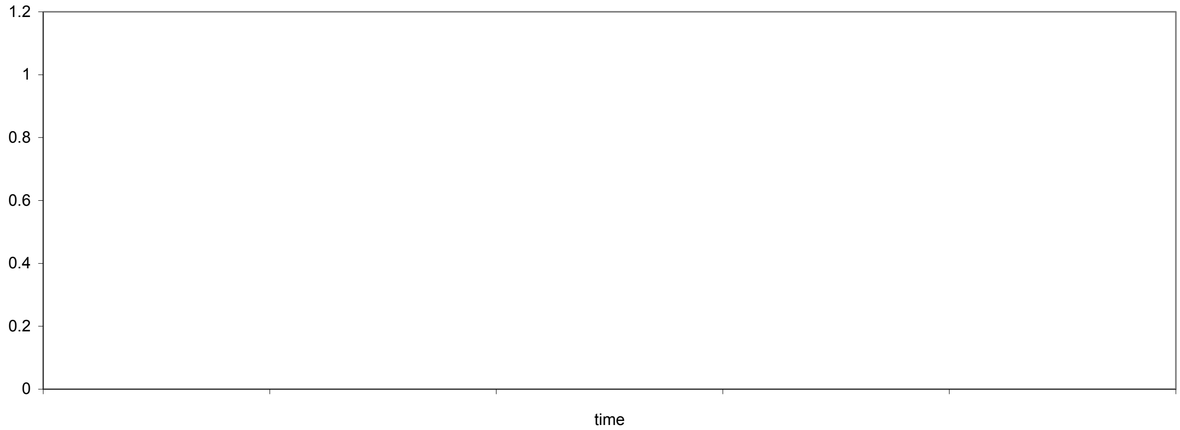

Figure: Time-series of reactive power set-point values and measured reactive power during reactive power set point step change

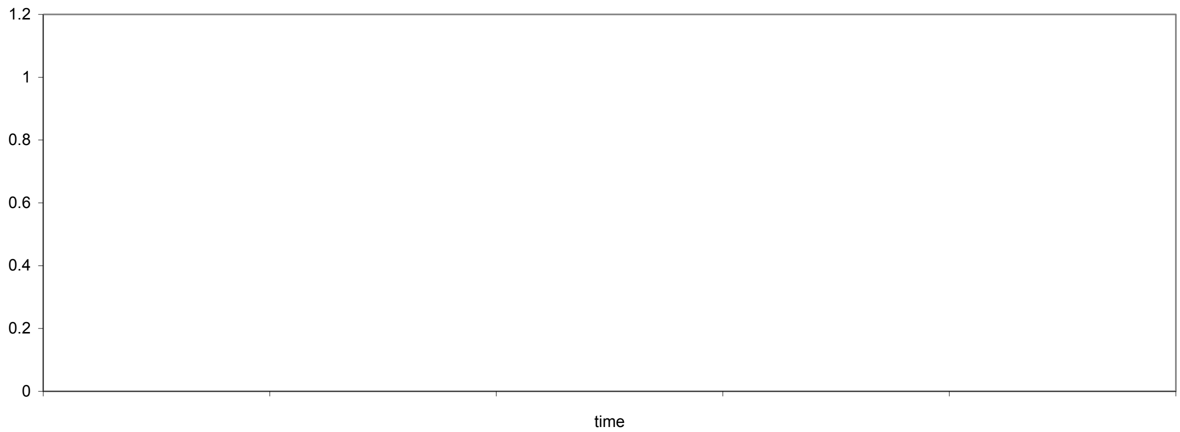

Figure: Time-series of active power during reactive power set point step change

Wind turbine type:		Sheet:		page 10 of 22

Grid Protection:

	Protection level		Disconnection time	
	Set point	**Measured**	**Set point**	**Measured**
Overvoltage				
Undervoltage				
Overfrequency				
Underfrequency				

Reconnection time:

Duration of grid failure [s]	10	60	600
Actual measured duration of grid failure [s]			
Reconnection time [s]			

Wind turbine type:		Sheet:		page 11 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Between 0,1 P_n and 0.3 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD1 – symmetrical three phase voltage dip	0,90 ± 0,05	0,90 ± 0,05	0,5 ± 0,02	¯¯¯¯|__|¯¯¯

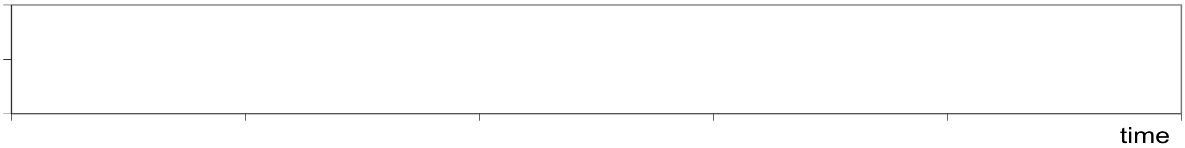

Figure: measured voltage drop when the wind turbine under test is not connected.

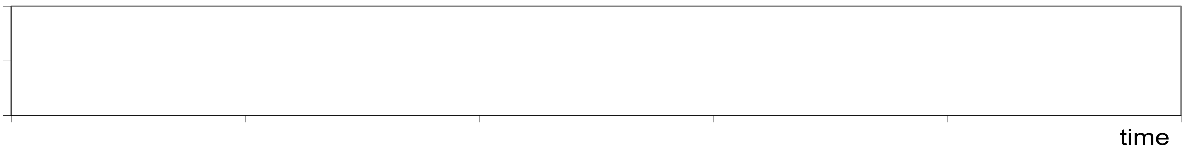

Figure: measured pos. sequence fundamental active power

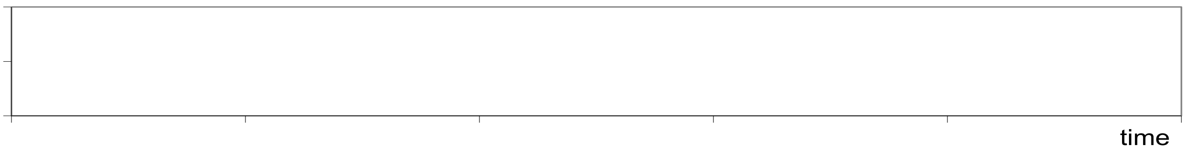

Figure: measured pos. sequence fundamental reactive power

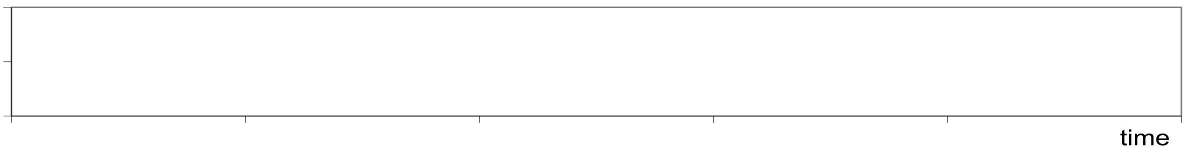

Figure: measured pos. sequence fundamental active current

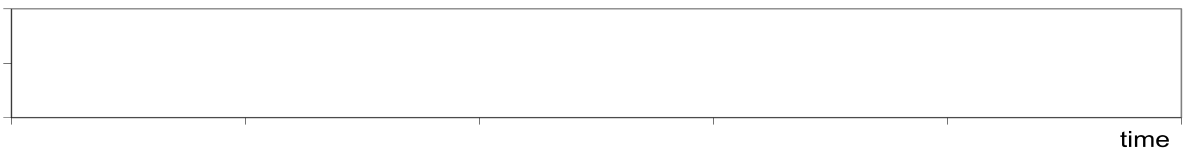

Figure: measured pos. sequence fundamental reactive current

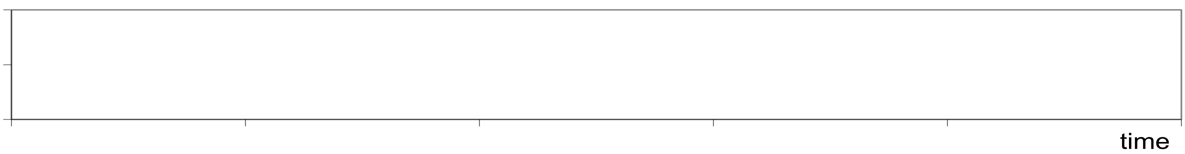

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

Wind turbine type:		Sheet:		page 12 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Above 0,9 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD1 – symmetrical three phase voltage dip	0,90 ± 0,05	0,90 ± 0,05	0,5 ± 0,02	¯¯¯|__|¯¯¯

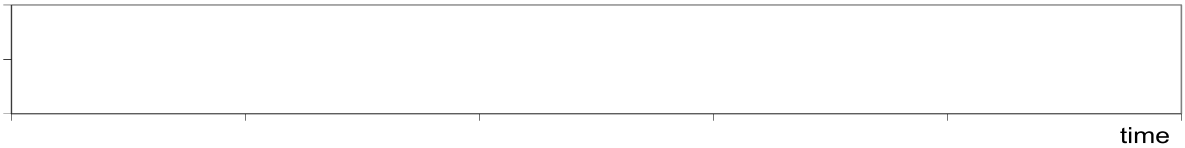

Figure: measured voltage drop when the wind turbine under test is not connected.

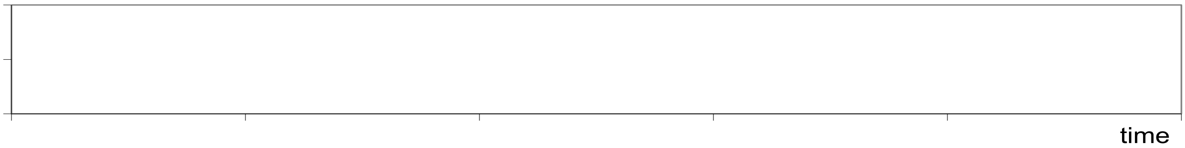

Figure: measured pos. sequence fundamental active power

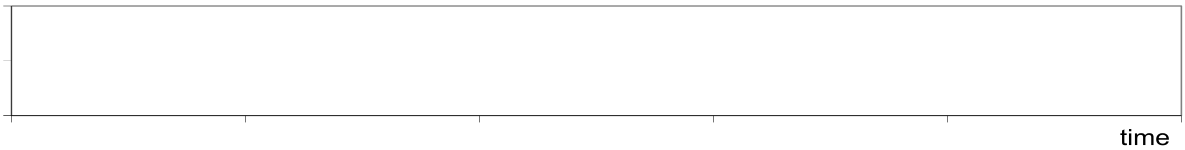

Figure: measured pos. sequence fundamental reactive power

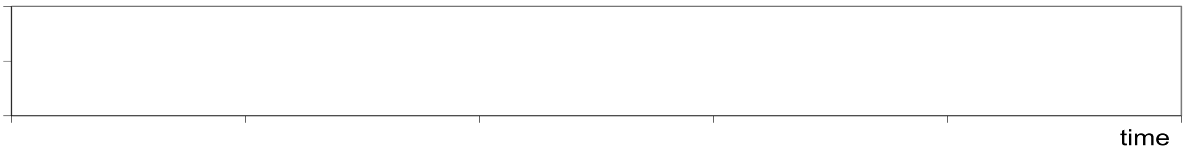

Figure: measured pos. sequence fundamental active current

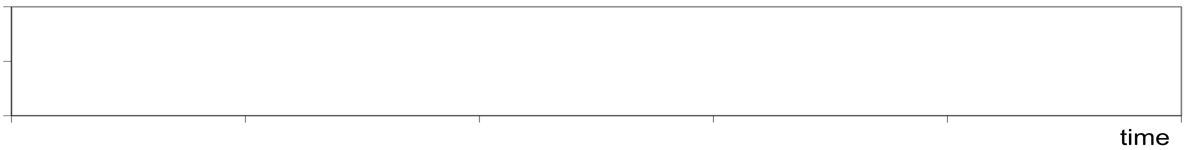

Figure: measured pos. sequence fundamental reactive current

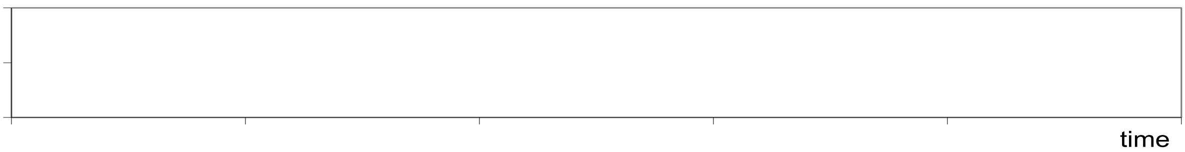

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

Wind turbine type:		Sheet:		page 13 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Between 0,1 P_n and 0.3 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD2 – symmetrical three phase voltage dip	0,50 ± 0,05	0,50 ± 0,05	0,5 ± 0,02	¯¯¯¯|__|¯¯¯

time

Figure: measured voltage drop when the wind turbine under test is not connected.

time

Figure: measured pos. sequence fundamental active power

time

Figure: measured pos. sequence fundamental reactive power

time

Figure: measured pos. sequence fundamental active current

time

Figure: measured pos. sequence fundamental reactive current

time

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

DATA SHEET OF POWER QUALITY MEASUREMENT

According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 14 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Above 0,9 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD2 – symmetrical three phase voltage dip	0,50 ± 0,05	0,50 ± 0,05	0,5 ± 0,02	‾‾‾‾|__|‾‾‾

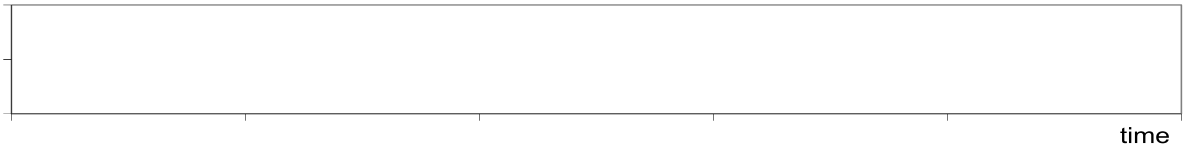

Figure: measured voltage drop when the wind turbine under test is not connected.

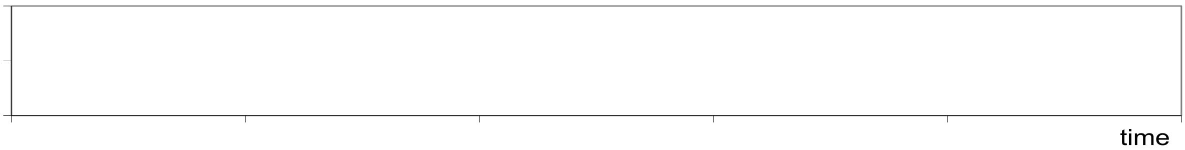

Figure: measured pos. sequence fundamental active power

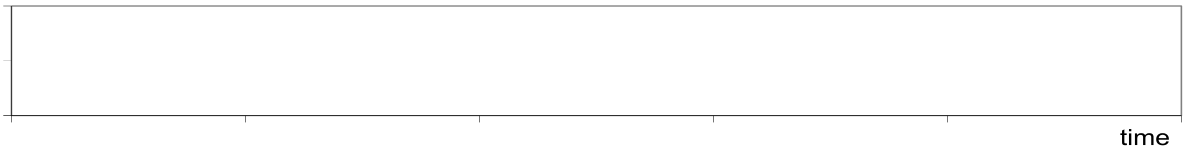

Figure: measured pos. sequence fundamental reactive power

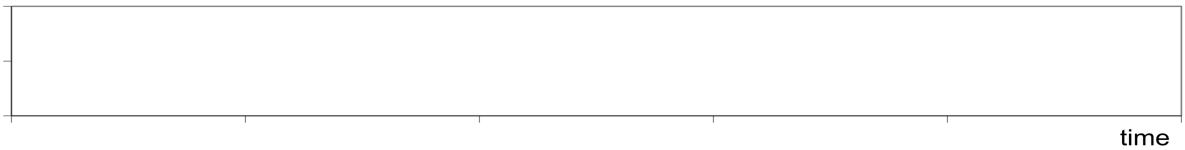

Figure: measured pos. sequence fundamental active current

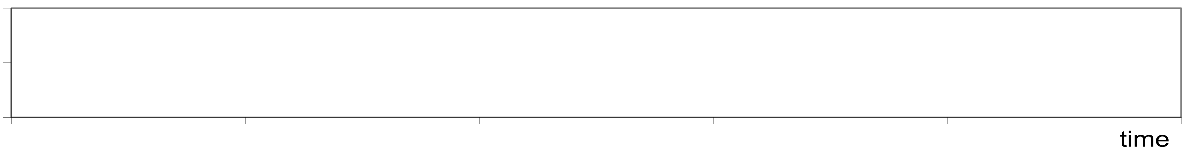

Figure: measured pos. sequence fundamental reactive current

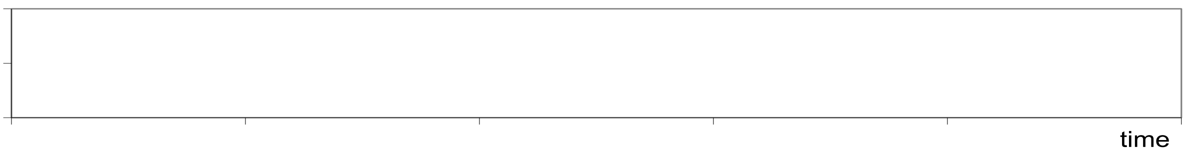

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

Wind turbine type:		Sheet:		page 15 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Between 0,1 P_n and 0.3 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD3 – symmetrical three phase voltage dip	0,20 ± 0,05	0,20 ± 0,05	0,2 ± 0,02	¯¯¯¯|__|¯¯¯

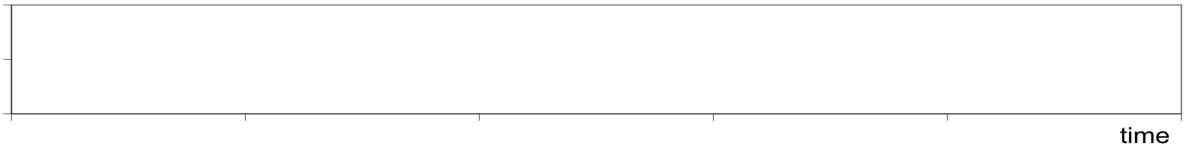

Figure: measured voltage drop when the wind turbine under test is not connected.

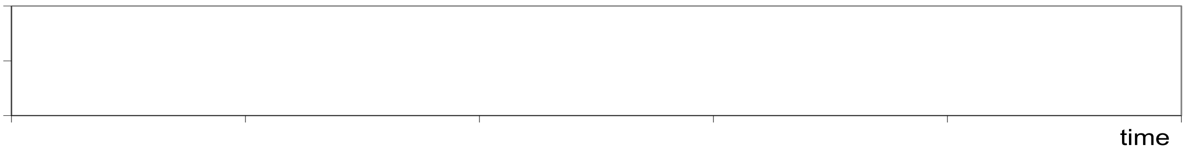

Figure: measured pos. sequence fundamental active power

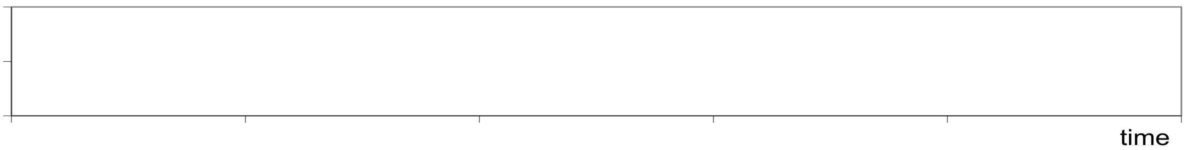

Figure: measured pos. sequence fundamental reactive power

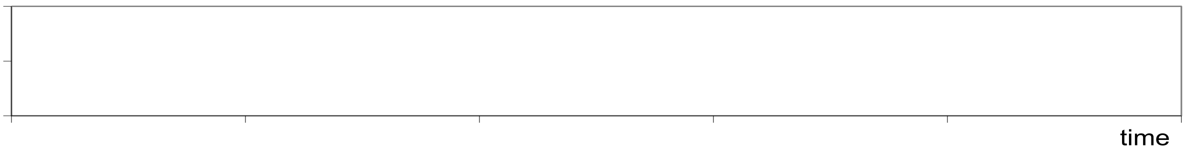

Figure: measured pos. sequence fundamental active current

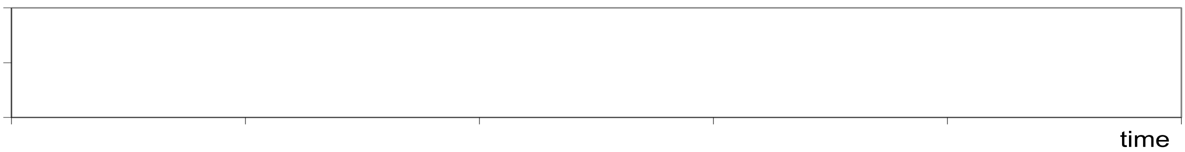

Figure: measured pos. sequence fundamental reactive current

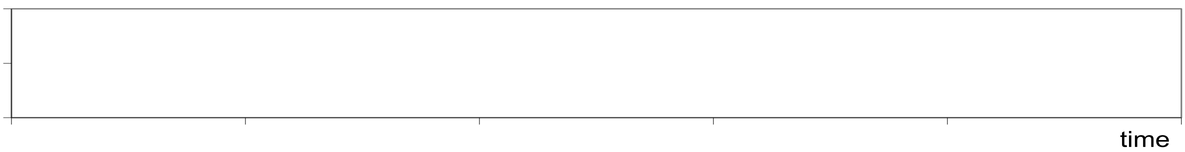

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

Wind turbine type:		Sheet:		page 16 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Above 0,9 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD3 – symmetrical three phase voltage dip	0,20 ± 0,05	0,20 ± 0,05	0,2 ± 0,02	‾‾‾|__|‾‾‾

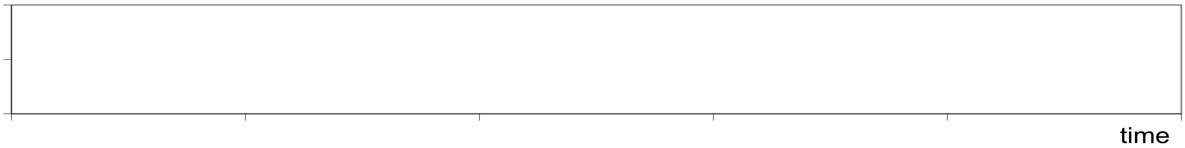

Figure: measured voltage drop when the wind turbine under test is not connected.

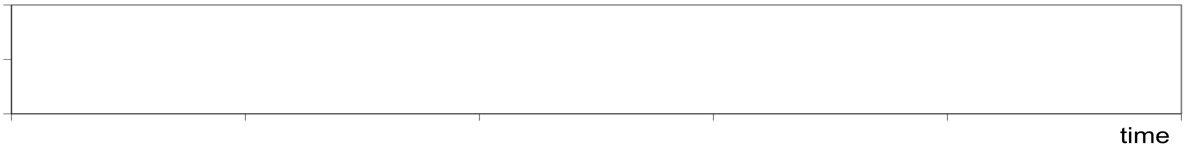

Figure: measured pos. sequence fundamental active power

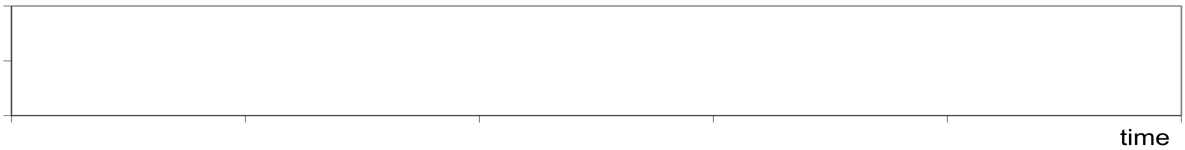

Figure: measured pos. sequence fundamental reactive power

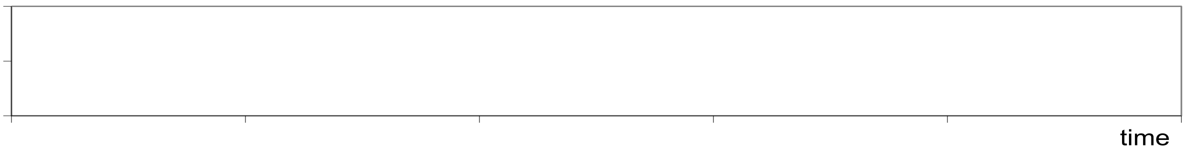

Figure: measured pos. sequence fundamental active current

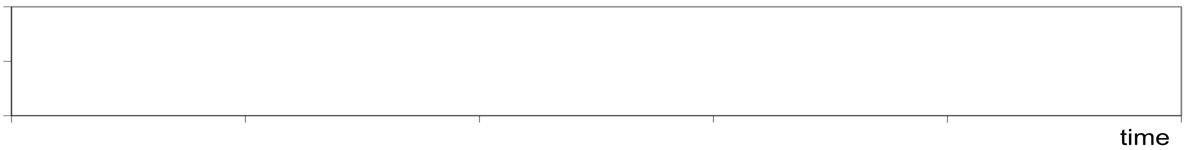

Figure: measured pos. sequence fundamental reactive current

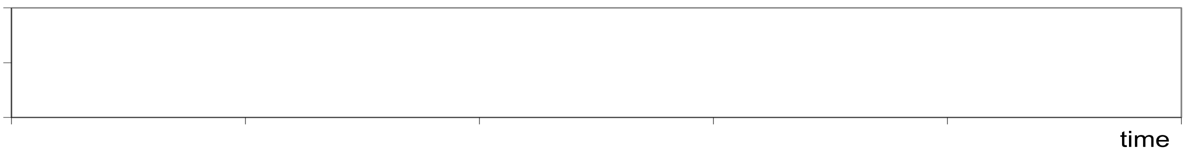

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

DATA SHEET OF POWER QUALITY MEASUREMENT
According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 17 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Between 0,1 P_n and 0.3 P_n

<table>
<tr><th rowspan="2">Case</th><th colspan="2">Magnitude of voltage (fraction of voltage immediately before the drop occurs)</th><th rowspan="2">Duration (s)</th><th rowspan="2">Shape</th></tr>
<tr><th>Phase to phase</th><th>Phase to ground</th></tr>
<tr><td>VD4 – two-phase voltage dip</td><td>0,90 ± 0,05</td><td>0,95 ± 0,05</td><td>0,5 ± 0,02</td><td>¯¯¯|__|¯¯¯</td></tr>
</table>

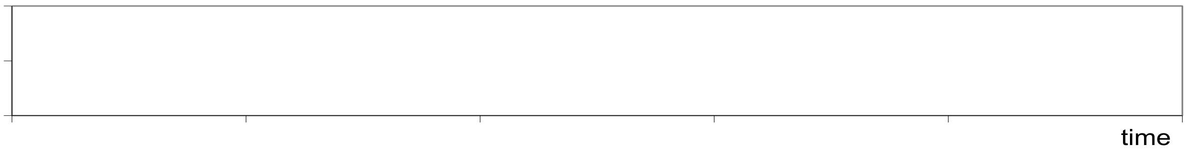

Figure: measured voltage drop when the wind turbine under test is not connected.

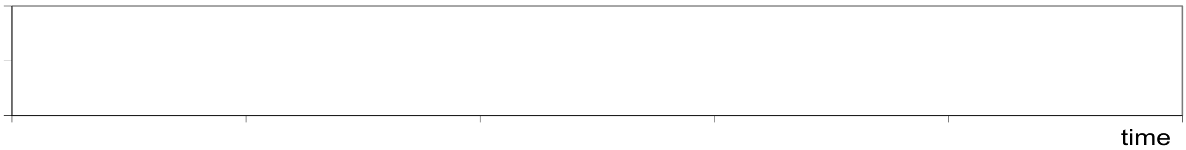

Figure: measured pos. sequence fundamental active power

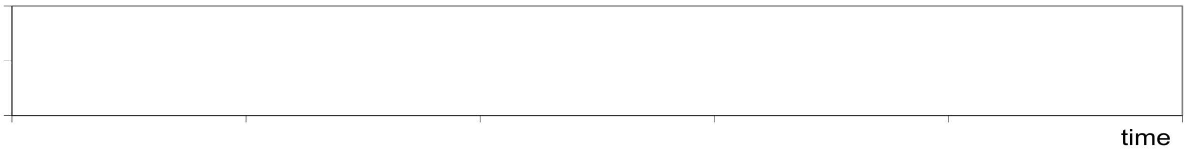

Figure: measured pos. sequence fundamental reactive power

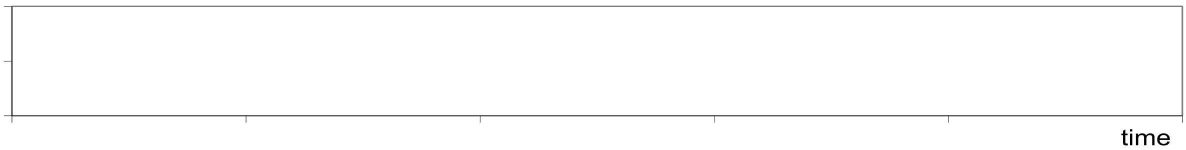

Figure: measured pos. sequence fundamental active current

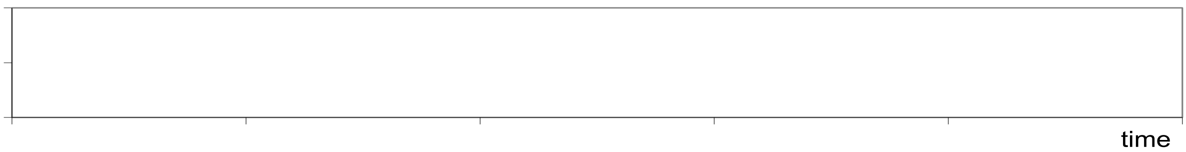

Figure: measured pos. sequence fundamental reactive current

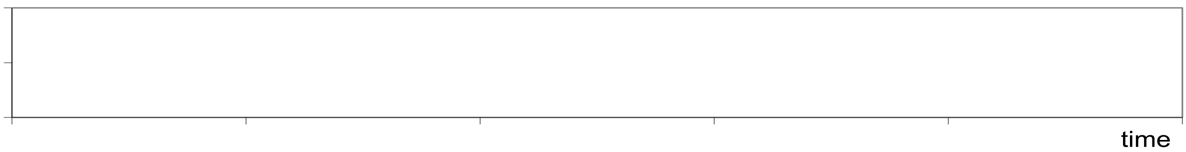

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

DATA SHEET OF POWER QUALITY MEASUREMENT

According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 18 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Above 0,9 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD4 – two-phase voltage dip	0,90 ± 0,05	0,95 ± 0,05	0,5 ± 0,02	¯¯¯|__|¯¯¯

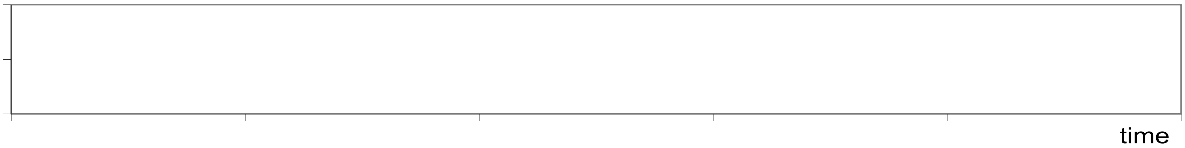

Figure: measured voltage drop when the wind turbine under test is not connected.

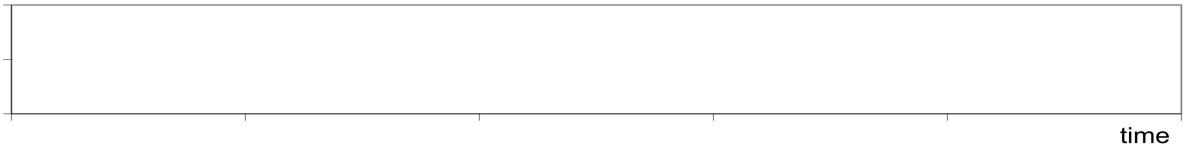

Figure: measured pos. sequence fundamental active power

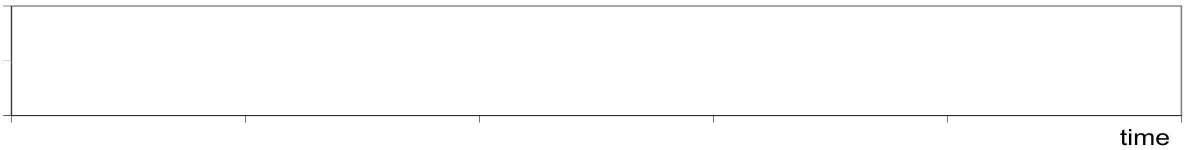

Figure: measured pos. sequence fundamental reactive power

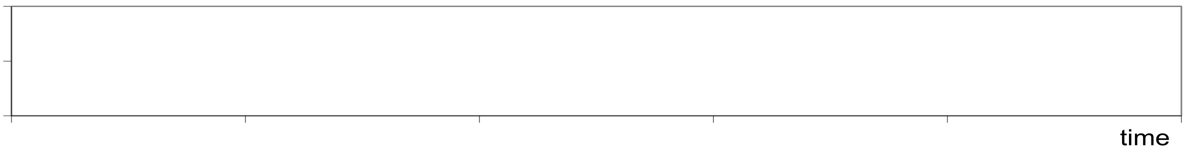

Figure: measured pos. sequence fundamental active current

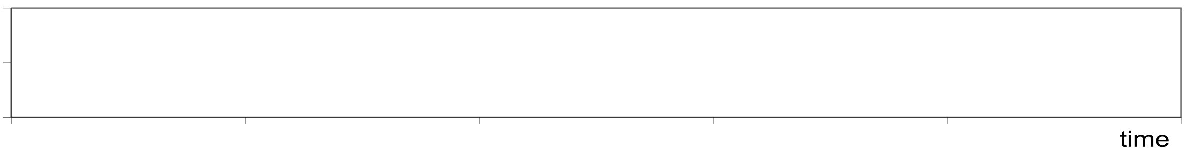

Figure: measured pos. sequence fundamental reactive current

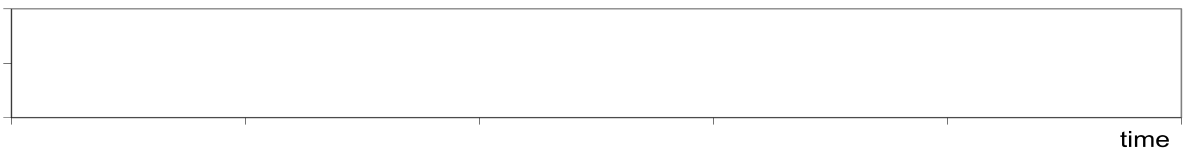

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

DATA SHEET OF POWER QUALITY MEASUREMENT
According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 19 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Between 0,1 P_n and 0.3 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD5 – two-phase voltage dip	0,50 ± 0,05	0,75 ± 0,05	0,5 ± 0,02	‾‾‾|__|‾‾‾

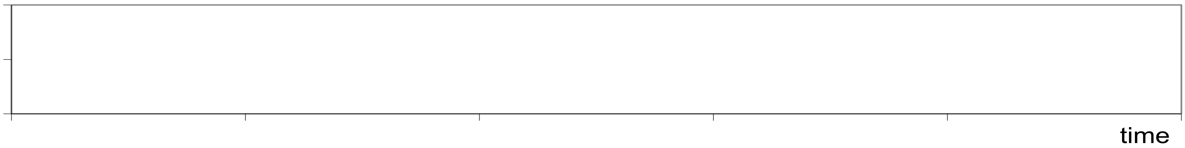

Figure: measured voltage drop when the wind turbine under test is not connected.

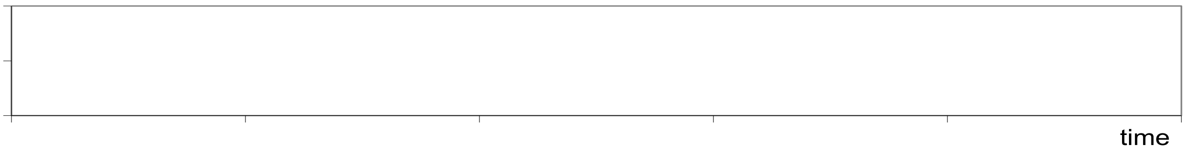

Figure: measured pos. sequence fundamental active power

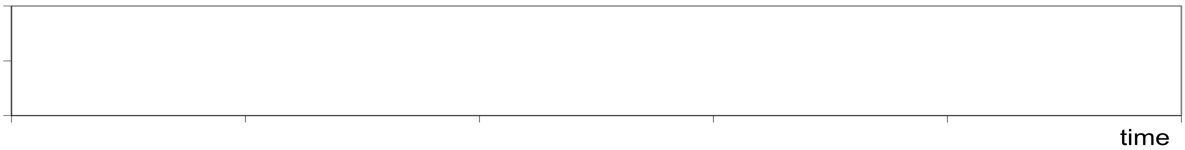

Figure: measured pos. sequence fundamental reactive power

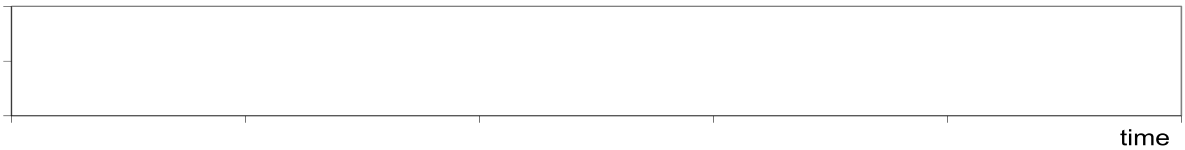

Figure: measured pos. sequence fundamental active current

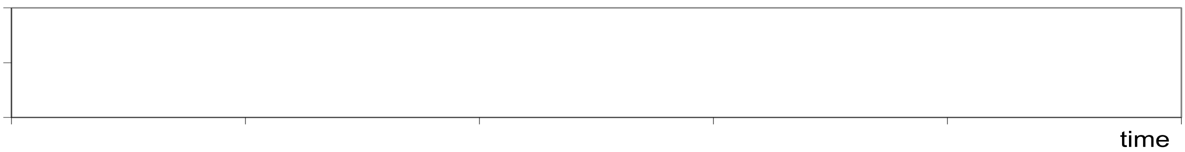

Figure: measured pos. sequence fundamental reactive current

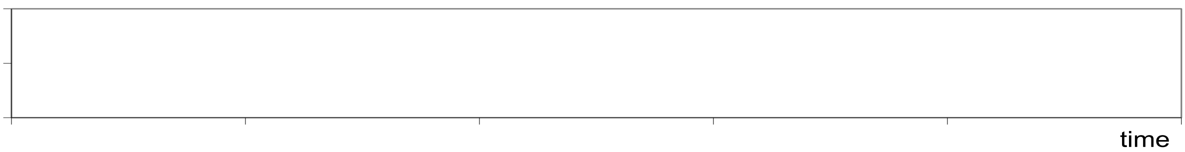

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

DATA SHEET OF POWER QUALITY MEASUREMENT
According to Measnet Power Quality Procedure, Version 4

Wind turbine type:		Sheet:		page 20 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Above 0,9 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD5 – two-phase voltage dip	0,50 ± 0,05	0,75 ± 0,05	0,5 ± 0,02	¯¯¯¯|__|¯¯¯¯

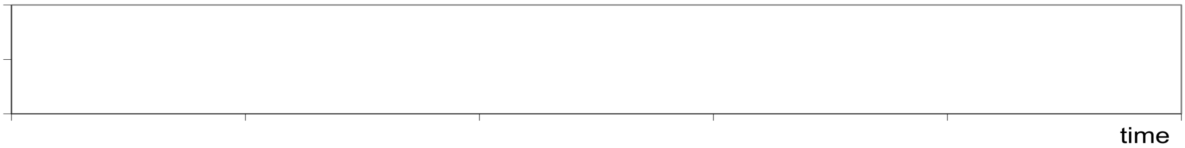

Figure: measured voltage drop when the wind turbine under test is not connected.

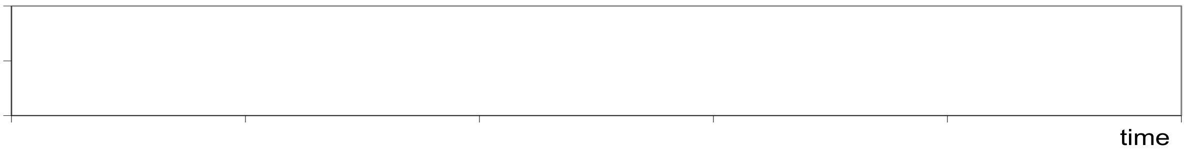

Figure: measured pos. sequence fundamental active power

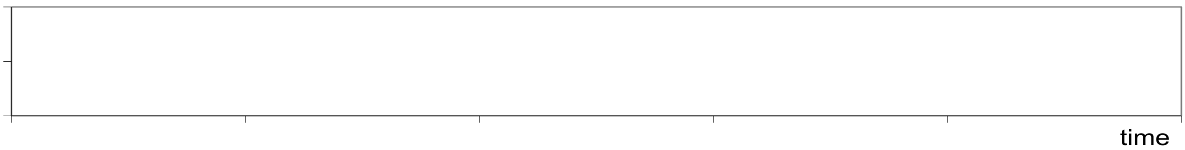

Figure: measured pos. sequence fundamental reactive power

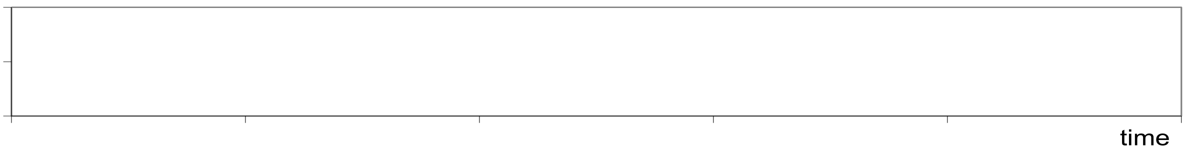

Figure: measured pos. sequence fundamental active current

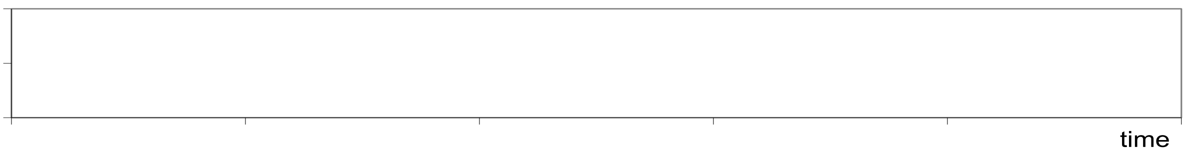

Figure: measured pos. sequence fundamental reactive current

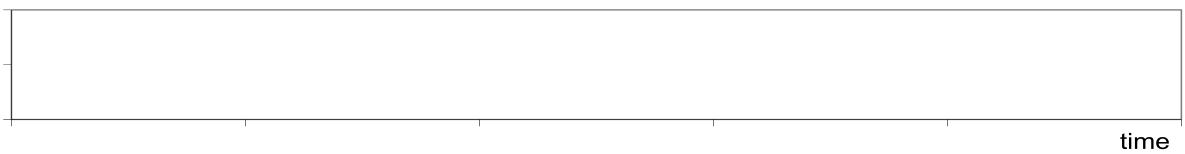

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

Wind turbine type:		Sheet:		page 21 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Between 0,1 P_n and 0.3 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD6 – two-phase voltage dip	0,20 ± 0,05	0,6 ± 0,05	0,2 ± 0,02	¯¯¯¯|__|¯¯¯

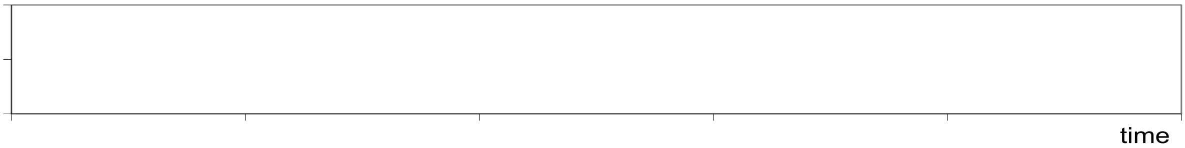

Figure: measured voltage drop when the wind turbine under test is not connected.

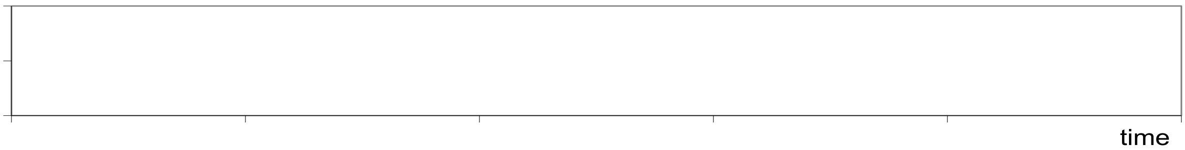

Figure: measured pos. sequence fundamental active power

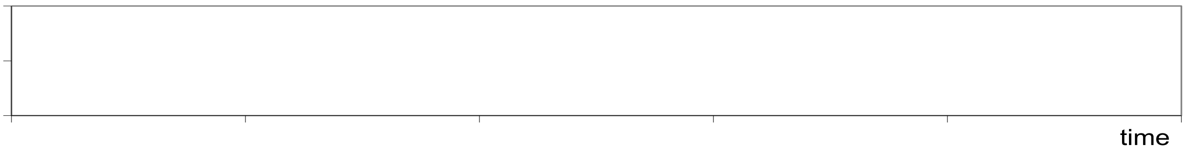

Figure: measured pos. sequence fundamental reactive power

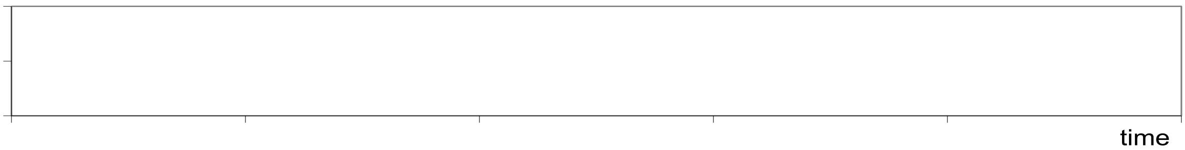

Figure: measured pos. sequence fundamental active current

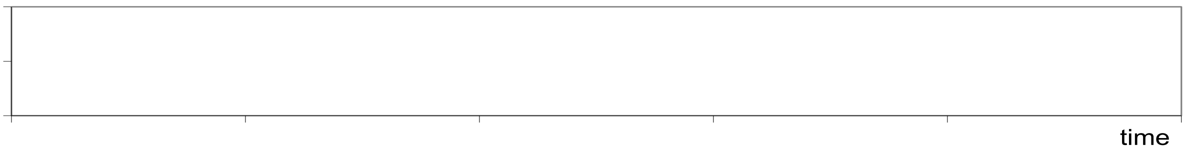

Figure: measured pos. sequence fundamental reactive current

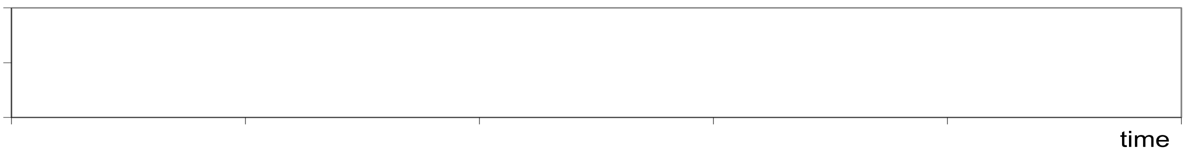

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

Wind turbine type:		Sheet:		page 22 of 22

Response to voltage drops:

Operational mode of the wind turbine during the test	
Active power range	Above 0,9 P_n

Case	Magnitude of voltage (fraction of voltage immediately before the drop occurs)		Duration (s)	Shape
	Phase to phase	Phase to ground		
VD6 – two-phase voltage dip	0,20 ± 0,05	0,6 ± 0,05	0,2 ± 0,02	‾‾‾|__|‾‾‾

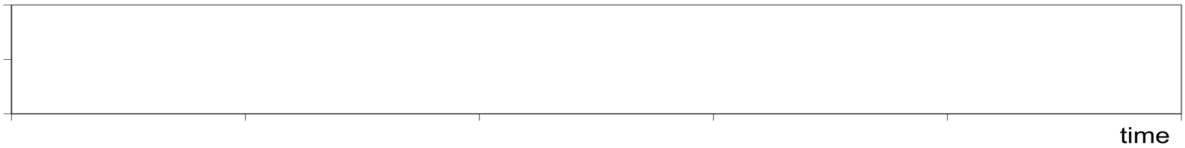

Figure: measured voltage drop when the wind turbine under test is not connected.

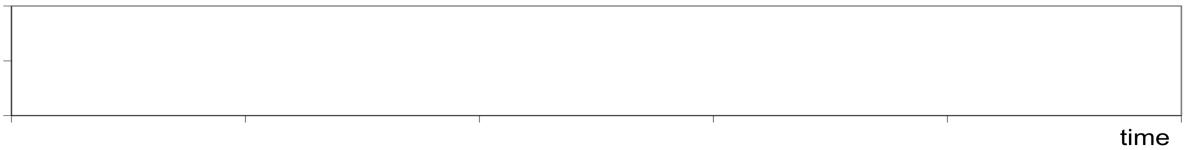

Figure: measured pos. sequence fundamental active power

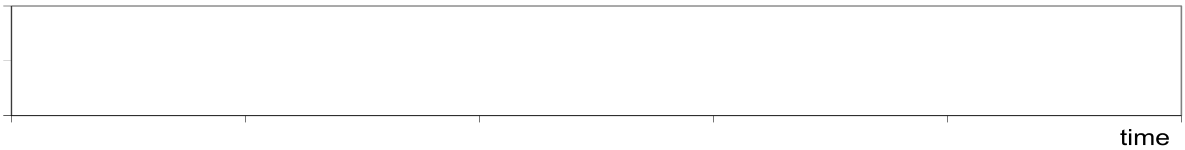

Figure: measured pos. sequence fundamental reactive power

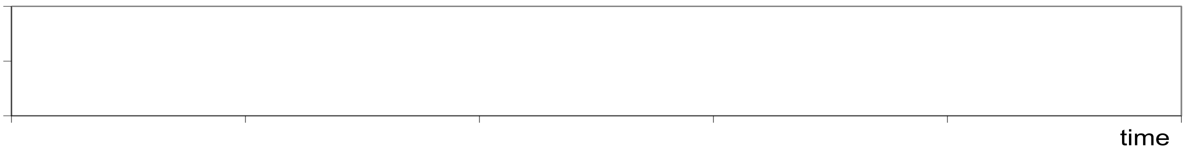

Figure: measured pos. sequence fundamental active current

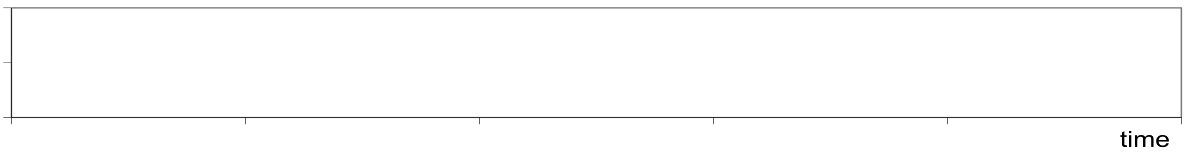

Figure: measured pos. sequence fundamental reactive current

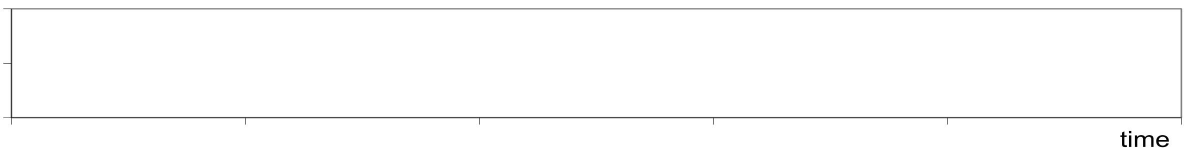

Figure: measured pos. sequence fundamental voltage at wind turbine terminals

B.1 Sources of uncertainty in wind turbine power quality measurements

It is a requirement for each accredited certification laboratory worldwide to accompany their test reports with a statement describing the uncertainty associated with test results. The main measured parameters in power quality testing of wind turbines are voltages, currents and wind speed. The other PQ parameters such as active and reactive powers, flicker and harmonics are calculated from main parameters.

The uncertainty of the wind speed measurements is a combination of several uncertainty components. This uncertainty is addressed in [1] based on site calibrations and anemometer characteristics. Following IEC 61400-21, chapter 7.1.3 a correction of the wind speed signal with the power curve is necessary, if the anemometer of the nacelle is used.

Uncertainty of AC measurements comprises many components. There are various sources of uncertainty that influence AC voltage and current measurements such as changes in the characteristics of transducers since last calibration, varying environmental conditions, electrical noise, transducer ratio and phase errors, and linearity. The data acquisition system uncertainty is related to offset, gain, quantization, noise, linearity, cross talk, and temperature drift specific to particular A/D converter.

The propagation of uncertainties through the calculation chain in combination with uncertainties introduced by numerical algorithms may have an effect on accuracy of calculated PQ characteristics such as RMS values, frequency, reactive power, harmonic components, flicker, etc. Such uncertainties need to be evaluated and quantified as well.

B.2 Types of uncertainty

The procedures and guidance for uncertainty estimation are contained in [2]. There are two types of uncertainty. **Type A uncertainty** is associated with the statistical distribution of measurements. Type B uncertainty is associated with systematic errors and can be estimated using data provided in instrument calibrations and manufacturer specifications. The total uncertainty of a measurement is a combination of both types. In the process of defining an uncertainty budget all of the most important contributors to uncertainty in the measurement must be considered, defined and normalized to standard uncertainty.

The general way of estimating Type A uncertainty of measured data set X is by calculating the standard deviation σ. Then the standard Type A uncertainty can be estimated as

$$\boldsymbol{U_A} = \frac{\sigma}{\sqrt{n}} \qquad (1)$$

Where n is number of measurements in the data set X.

A **Type B uncertainty** is introduced by measuring instruments and can be evaluated from manufacturer specifications and calibration certificates. This information usually allows estimating accuracy for only upper and lower limits of measurement range. It is assumed in [2] that a probability distribution with constant probability density between limits (rectangular probability distribution) can be used for possible variability of the measured quantity. This is taken into account by dividing the Type B standard uncertainty by $\sqrt{3}$.

The analog measuring instruments are usually specified by class of accuracy (for example 0.2, 0.5,1, etc.) The class of accuracy means that the absolute uncertainty of the instrument does not exceed the class number in % with relation to full scale value. Some manufacturers express accuracy of instrument in the form of ±(gain error + offset error).

The accuracy of digital instruments and A/D converters is usually described as ±(%reading + %Full Scale), ±(%reading + %range) or ±(ppm reading + ppm range). The uncertainty associated with accuracy of measurement is contributed by %Full Scale, %range or ppm range. The uncertainty associated with resolution is contributed by %reading or ppm reading.

Sometimes information about sensor nonlinearity is given by manufacturer or can be obtained from calibration data. In such case, the uncertainty introduced by non-linearity must be estimated as well.

Uncertainty contributions from all sources must be in the same units before they are combined (usually in the units of measured signal). For example, the uncertainty in wind turbine line voltage measurements must be expressed in volts. The total Type B uncertainty then can be calculated as

$$U_B = \frac{1}{\sqrt{3}}\sqrt{\sum u_{B,k}^2} \qquad (2)$$

Where $u_{B,k}$ is individual Type B uncertainty component, U_B is total combined Type B uncertainty. The equation 2 assumes unity sensitivity coefficients for all $u_{B,k}$ components.

B.3 Evaluation of Type B Uncertainty

For the completeness of the analysis, it is required that an evaluation of Type B Uncertainty is performed. According to the previous paragraphs, the main sources of Type B uncertainty during the measurement procedure are the following:

1. Current and voltage transformers
2. Power quality measuring system
3. A/D card
4. Software

The uncertainty values, calculated according to [2], are presented in Table B1 and they are applicable to all tests assuming the typical error of each instrument as specified in the second column of Table B1.

Table B1. Estimated Type B uncertainty in power quality measurements

Error source	Assumptions	Uncertainty value, u_i
u_{CT}, Uncertainty of current transformers (as in IEC 61400-12-1)	• Transformers class 1/IEC-61400-21 • The typical error according to the instrument's accuracy class is considered equal to e_{CT}% of full-scale current (Conservative approach). • One transformer at each phase, uniform load per phase • Completely correlated errors from all three transformers • Calibration error is included in the above error (accuracy class) • Typical error follows a rectangular distribution	$u_{CT} = \frac{e_{CT}}{100 \cdot \sqrt{3}} \cdot I$ (Amps)
u_{VT}, Uncertainty of voltage transformers (as in 61400-12-1)	• Transformer class 1/ IEC-61400-21 • Typical transformer error equal to eVT% of full-scale voltage • Calibration error is included in the above error • Typical error follows a rectangular distribution	$u_{VT} = \frac{e_{VT}}{100 \cdot \sqrt{3}} \cdot V$ (Volts)
U_{FT}, Uncertainty of frequency transducer	• Typical transducer error equal to eFT% of centre frequency • Calibration error is included in the above error • Typical error follows a rectangular distribution	$u_{FT} = \frac{e_{FT}}{100 \cdot \sqrt{3}} \cdot f$ (Hz)
U_{PQ}, Uncertainty of PQ measuring system	• Typical PQ system error equal to ePQ% of full scale of the measured quantity (MQ) • Typical error follows a rectangular distribution	$u_{PQ} = \frac{e_{PQ}}{100 \cdot \sqrt{3}} \cdot MQ$ (Units)
$u_{PQ\text{-}cal}$, Uncertainty of PQ measuring system calibration	• Uncertainty in reference instruments as from calibration report	As specified in the calibration report
u_{DAQ}, Uncertainty of A/D Card	• Typical n-bit A/D card error equal to 1/2n of full scale input range • Typical error follows a rectangular distribution	$u_{DAQ} = \frac{\text{FullScaleInoutRange}}{2^n \cdot \sqrt{3}} \cdot \frac{\partial(MQ)}{\partial(\text{Input})}$
u_A, Total uncertainty in current measurement	• $u_A = \sqrt{u_{CT}^2 + u_{PQ}^2 + u_{PQ-cal}^2 + u_{DAQ}^2}$ • Typical error follows a rectangular distribution	u_A (Amps)
u_V, Total uncertainty in voltage measurement	• $u_V = \sqrt{u_{VT}^2 + u_{PQ}^2 + u_{PQ-cal}^2 + u_{DAQ}^2}$ • Typical error follows a rectangular distribution	u_V (Volts)
u_P, Uncertainty in active power calculation	• In each phase: $u_{P_i} = \sqrt{\left(\frac{\partial P_i}{\partial I_i} \cdot u_{A_i}\right)^2 + \left(\frac{\partial P_i}{\partial V_i} \cdot u_{V_i}\right)^2}$ • Total: $u_P = \sqrt{\sum_{i=1}^{3} u_{P_i}^2}$ • Typical error follows a rectangular distribution	u_P (kW)
u_Q, Uncertainty in reactive power calculation	• Typical error in reactive power calculation equal to eQ % of rated reactive power, estimated by sensitivity analysis of experimental data. • Typical error follows a rectangular distribution	$u_Q = \frac{e_Q}{100 \cdot \sqrt{3}} \cdot Q_{rated}$ (kVar)
u_{FL}, Uncertainty in flicker calculation	• Typical error in flicker coefficient calculation equal to ef % estimated by sensitivity analysis of experimental data. • Typical error follows a rectangular distribution	$u_{FL} = \frac{e_f}{100 \cdot \sqrt{3}}$ (Non dimensional)
u_H, Uncertainty in the calculation of harmonic currents	• The Nyquist criterion is followed, which states that the sampling rate must be at least twice as fast as the highest frequency component in the input signal. • Maximum error in sampling rate equal to eH % of rated current, estimated by sensitivity analysis of experimental data. • Maximum error depends on harmonic current frequency • Typical error follows a rectangular distribution	$u_H = \frac{e_H}{100 \cdot \sqrt{3}} \cdot I_{rated}$ (Amps)

An example of type B uncertainty calculation for measurements using 1000 V (full scale RMS) voltage transducer and DAS device is given in Table B2. The total Type B expanded uncertainty for this measurement is estimated at 6.938V at 95% confidence interval.

Table B2: Example Type B uncertainty calculation for voltage measurements

Source of uncertainty	Value	Probability Distribution	Divisor	Sensitivity	Standard Uncertainty (Volts)
Sensor gain error	0.6%	Rectangular	$\sqrt{3}$	1	3.464
Sensor offset error	0.013%	Rectangular	$\sqrt{3}$	1	0.075
DAS % of reading	0.03%	Rectangular	$\sqrt{3}$	1	0.173
DAS % of full scale	0.008%	Rectangular	$\sqrt{3}$	1	0.046
Combined standard uncertainty:					3.469
Expanded uncertainty at 95% confidence level (k=2):					6.938

Similarly, Type B uncertainty can be estimated for current measurement channel as well. An example for current measurement uncertainty using 3000 A current probes (1mV/A) is given in Table B3.

Table B3: Example of Type B uncertainty calculation for current measurements

Source of uncertainty	Value	Probability Distribution	Divisor	Sensitivity	Standard Uncertainty (Amps)
Sensor gain error	1%	Rectangular	$\sqrt{3}$	1	17.32
Sensor linearity error	0.2%	Rectangular	$\sqrt{3}$	1	3.46
Noise	8 mV	Rectangular	$\sqrt{3}$	1	4.62
DAS % of reading	0.03%	Rectangular	$\sqrt{3}$	1	0.52
DAS % of full scale	0.008%	Rectangular	$\sqrt{3}$	1	0.138
Combined standard uncertainty:					18.26
Expanded uncertainty at 95% confidence level (k=2):					36.52

In case if power measurements are conducted using dedicated power transducer, the Type B uncertainty in power measurement can be estimated using the same method as for voltage and current.

Both instrument transformers and DAS devices have phase shifts. An example of uncertainty calculation for phase angle is shown in Table B4.

Table B4: Example of Type B uncertainty calculation for phase angle

Source of uncertainty	Value	Probability Distribution	Divisor	Sensitivity	Standard Uncertainty (el. deg)
Voltage sensor phase error	0.002 deg	Rectangular	$\sqrt{3}$	1	0.001
Current sensor phase error	0.2 deg	Rectangular	$\sqrt{3}$	1	0.115
DAS phase error	0.003%	Rectangular	$\sqrt{3}$	1	0.002
Combined standard uncertainty:					0.115
Expanded uncertainty at 95% confidence level (k=2):					0.23

B.4 Evaluation of Total Uncertainty

The final step in the process is combining both types A and B for calculating total expanded uncertainty in the power quality measurements using the following equation.

$$U = 2\sqrt{U_A^2 + U_B^2} \qquad (3)$$

The total expanded uncertainty in equation 3 is obtained by multiplying the resulting standard uncertainty value by a factor of two (k=2), approximating 95% confidence level.