Power Quality Test Report for the U.S. Department of Energy 1.5-Megawatt Wind Turbine

Ismael Mendoza, Jerry Hur, and Syhoune Thao
National Renewable Energy Laboratory

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Technical Report
NREL/TP-5000-63686
August 2015

Contract No. DE-AC36-08GO28308

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Power Quality Test Report

for the

DOE 1.5-MW Wind Turbine

in

Golden, Colorado, USA

Conducted for

U.S. Department of Energy Office of Energy Efficiency and Renewable Energy
Wind and Water Power Program
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Conducted by

National Wind Technology Center
National Renewable Energy Laboratory
15013 Denver West Parkway
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Ismael Mendoza, Jerry Hur, and Simon Thao

February 24, 2015

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1 Background

The U.S. Department of Energy (DOE) acquired and installed a 1.5-megawatt (MW) wind turbine at the National Wind Technology Center (NWTC) at the National Renewable Energy Laboratory. This turbine (hereafter referred to as the DOE 1.5) is envisioned to become an integral part of the research initiatives for the DOE Wind Program, such as Atmosphere to Electrons (A2e). A2e is a multiyear DOE research initiative targeting significant reductions in the cost of wind energy through an improved understanding of the complex physics governing wind flow into and through wind farms. For more information, visit http://energy.gov/eere/wind/atmosphere-electrons.

To validate new and existing high-fidelity simulations, A2e must deploy several experimental measurement campaigns across different scales. Proposed experiments include wind tunnel tests, scaled field tests, and large field measurement campaigns at operating wind plants. Data of interest includes long-term atmospheric data sets, wind plant inflow, intra-wind plant flows (e.g., wakes), and rotor loads measurements. It is expected that new, high-fidelity instrumentation will be required to successfully collect data at the resolutions required to validate the high-fidelity simulations.

The large-scale field measurement campaigns are expected to use the DOE 1.5 as it is of sufficient enough size to represent current technology, and turbines of this size are widely deployed in U.S. wind plants.

Expected future use of the DOE 1.5 at the NWTC may include the following (leading up to the large files measurement campaigns at operating plants):

- Deployment and validation of high-fidelity instrumentation prior to large-scale deployment at a wind plant
- Deployment of advanced controls algorithms
- Characterization of inflow, aerodynamics, turbine loads, and wake propagation on an unwaked turbine.

A series of tests were conducted to characterize the baseline properties and performance of the DOE 1.5 to enable research model development and quantify the effects of future turbine research modifications.

The tests included:

- Power performance per International Electrotechnical Commission (IEC) 61400-12-1
- Power quality per IEC 61400-21
- Acoustic noise per IEC 61400-11

- Mechanical loads per IEC 61400-13
- Modal testing.

The DOE 1.5 is built on the platform of GE's 1.5-MW SLE commercial wind turbine model. It was installed in a nonstandard configuration at the NWTC with the objective of supporting DOE Wind Program research initiatives such as A2e. Therefore, the test results may not represent the performance capabilities of other GE 1.5-MW SLE turbines.

This report summarizes the analysis and results of the above-mentioned power quality test performed at the DOE 1.5.

2 Test Summary

The NWTC conducted this power quality test in accordance with the International Electrotechnical Commission standard, IEC61400-21, Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines, Edition 2.0, 2008-08 [1], hereafter referred to as the Standard. Standard procedures and the following test results required by the Standard are included in this report:

- Maximum measured power (600 seconds, 60 seconds, and 0.2 seconds)
- Reactive power demand
- Voltage fluctuations (flicker)
- Voltage harmonics, current harmonics, interharmonics, and distortions
- Turbine start and stop tests.

The DOE 1.5 power quality test began on March 15, 2011, and ended on May 2, 2011. 730 10-minute intervals of data were collected. The Standard requires at least five 10-minute averaged data points for each 1 m/s wind speed interval up to 15 m/s. The highest bin filled (without wind speed normalization) was the 16 m/s bin. When the data was binned by percent of rated power, more than 5 data points were recorded for each bin. According to the Standard, sufficient data was collected. The capture test matrix is shown in Table 1.

Table 1. Power Quality Capture Test Matrix Requirements Fulfilled

Test Type	Measured	Required by IEC 61400-21
Continuous operation: Number of 10-min intervals	Five for each bin	At least five for each 1-m/s wind speed bin up to 15 m/s
Switching operation: Number of wind turbine starts (cut-in wind speed)	Five	At least five
Switching operation: Number of wind turbine stops (cut-in wind speed)	Five	At least five
Switching operation: Number of wind turbine starts (rated wind speed)	Five	At least five
Switching operation: Number of wind turbine stops (rated wind speed)	Five	At least five

There were two identified exceptions to the Standard. The response to temporary voltage drop test and the grid protection test that are required by the second edition were not performed because the necessary test assets were not available in North America.

Also, because the necessary technical information was confidential and was not available from the manufacturer, the following tests were excluded from this testing campaign:

- Power control
- Voltage drop response
- Grid protection and reconnection.

3 Test Turbine Configuration

Table 2 to Table 4 list the technical data of the DOE 1.5 that was tested at the NWTC.

Table 2. DOE 1.5 General Data

Turbine manufacturer and address	GE Energy 300 Garlington Rd., P.O. Box 648 Greenville, SC 29602-0648
Model	GE 1.5 SLE
Serial number	N000780-N
Wind turbine type	Horizontal axis
Number of blades	3
Hub height (m)	80
Blade control	Pitch
Rotor diameter (m)	77
Speed control	variable
Generator type and rating (kW)	Asynchronous, 1500
Converter type	Unknown

Table 3. DOE 1.5-Rated Data

Rated power, P_n (kW)	1,500
Rated wind speed, V_n (m/s)	14
Rated apparent power, S_n (kVA)	1,666
Rated reactive power, Q_n (kvar)	+/-200
Rated current, I_n (A)	1,394
Rated voltage, V_n (V)	690
Rated frequency, f_n (Hz)	60

Table 4. DOE 1.5 Maximum Permitted Power

Peak continuous power, P_{mc} (kW)	1,545
Normalized value, $p_{mc}=P_{mc}/P_n$	1.03

Figure 1. DOE 1.5 at the NWTC. *Photo by Jeroen van Dam, NREL*

4 Test Site Description

The test turbine was located at Site 4.0 at the NWTC. The turbine provided power to the NWTC 10-MW utility power grid through a 0.690/13.2-kV transformer rated at 1,750 kVA. Figure 2shows the electrical site diagram, which indicates the placement of NREL's power quality instrumentation. Wind speed information was measured at hub height from the turbine meteorological tower 2.1 rotor diameters upstream, which is in compliance with the requirements from the Standard.

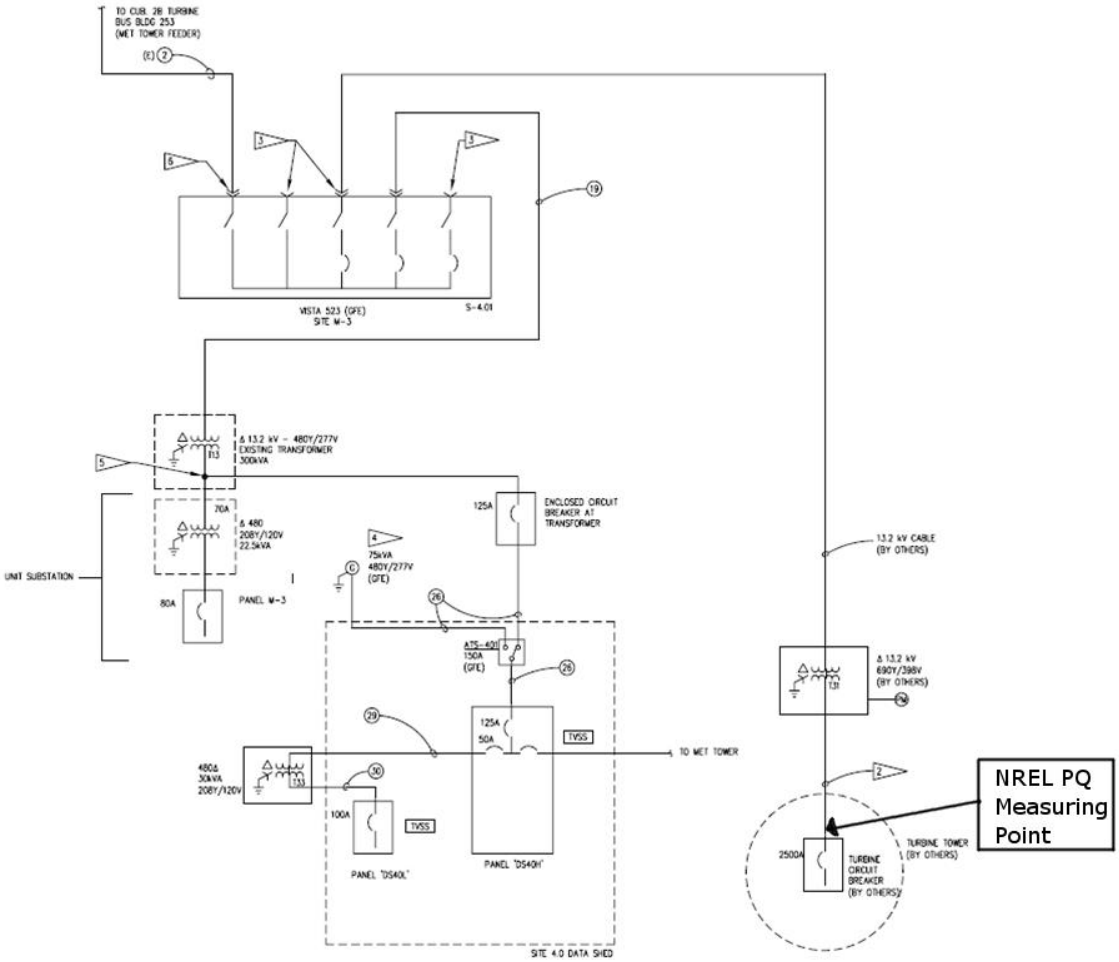


Figure 2. Site electrical diagram

5 Continuous Operation Test Results

5.1 Active and Reactive Power, Power Factor

The relationship between active and reactive power was measured at the wind turbine low voltage (0.690 kV) terminals. Time series measurements of voltage, current, and wind speed were taken during continuous operation. Using these data, 10-minute bin average statistics were calculated for each 1 m/s wind speed (in accordance with the Standard). Table 5 and Figure 3 show these results. The power factor (Figure 4) was calculated using active and reactive power values. Figure 5 shows the reactive power demand. Figure 6 illustrates the turbulence intensity observed during the testing period. Note that the active power curve shown in Figure 3 cannot be used for the DOE 1.5 power performance evaluation. The official power curve will be published in the DOE 1.5 power performance test report.

Table 5. Number of Data Points per 1-m/s Wind Speed Bins

Wind Speed Bin, m/s	Number of Valid 10-Min Data Points
0 to 1	0
1 to 2	0
2 to 3	8
3 to 4	81
4 to 5	92
5 to 6	106
6 to 7	92
7 to 8	75
8 to 9	64
9 to 10	65
10 to 11	44
11 to 12	47
12 to 13	23
13 to 14	16
14 to 15	5
15 to 16	5
16 to 17	4
17 to 18	3

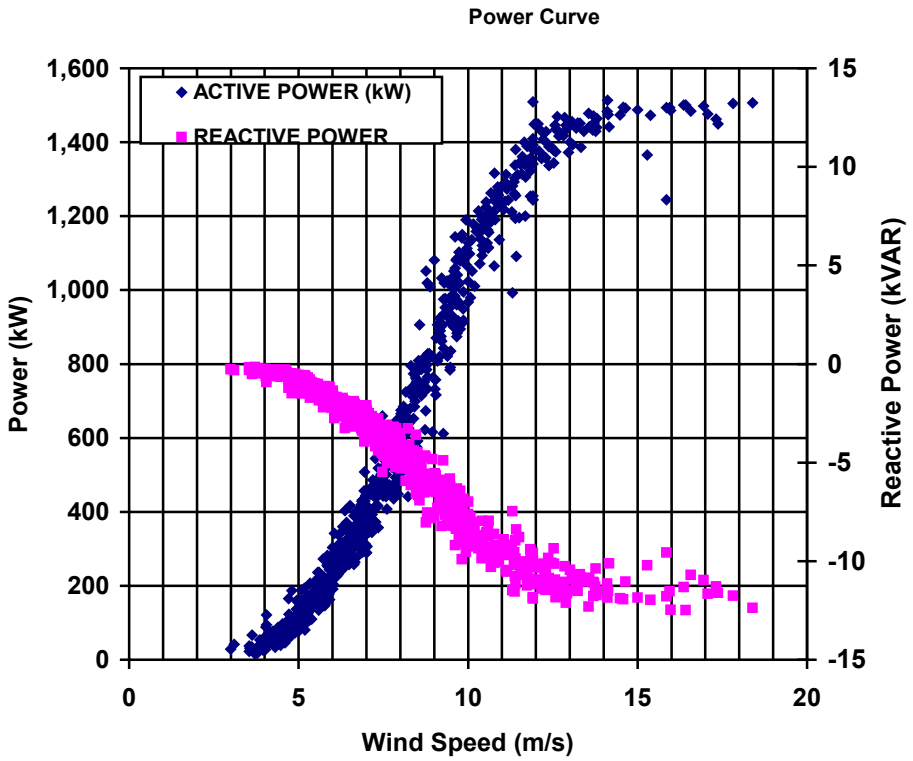


Figure 3. Active and reactive power versus wind speed

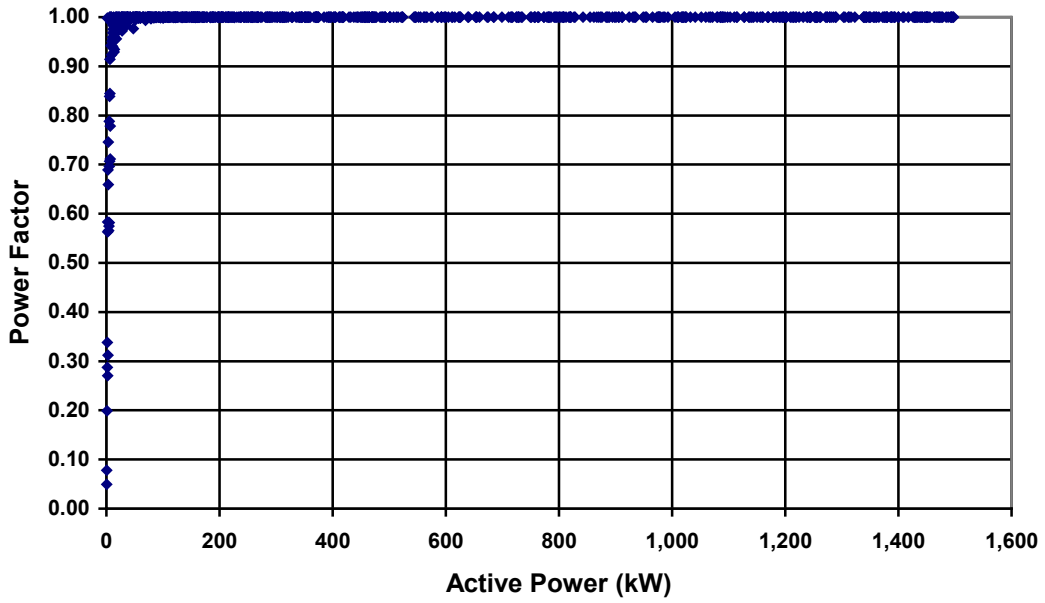


Figure 4. Power factor versus active power

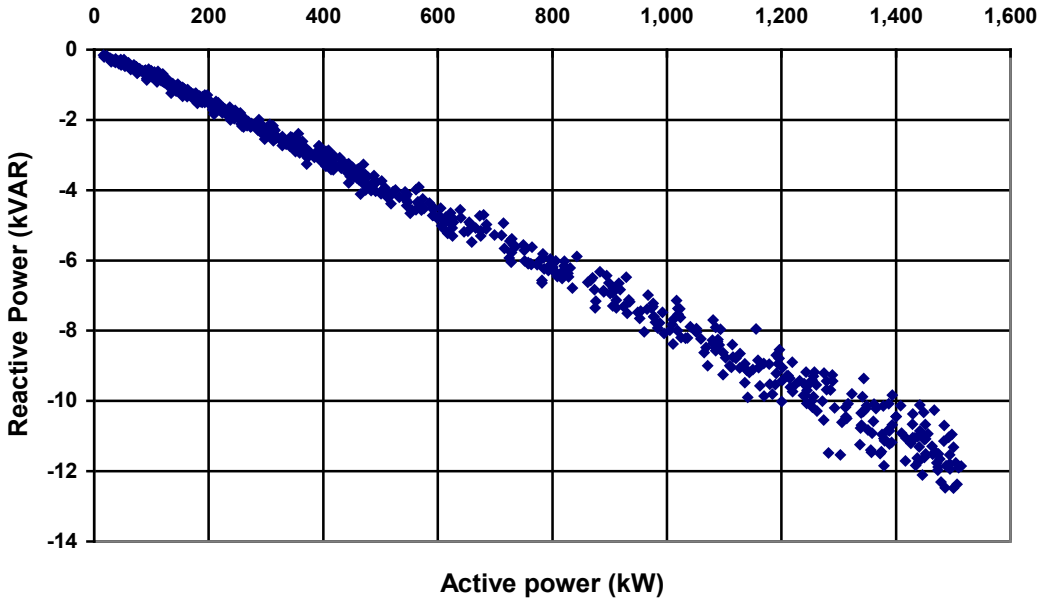


Figure 5. Reactive power versus active power

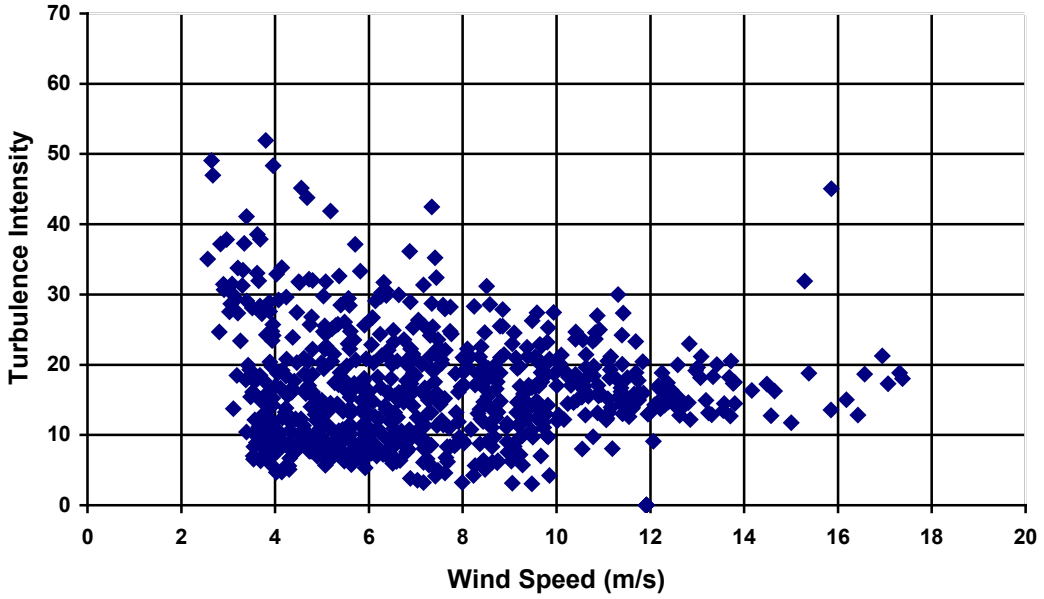


Figure 6. Turbulence intensity versus wind speed

The 10-minute reactive power average data were sorted by active power according to the method of bins and are shown in Table 6. The maximum active power statistics were taken from the 600 seconds (P_{600}), 60 seconds (P_{60}), and 0.2 seconds ($P_{0.2}$) values (Table 7). The reactive power at peak power (P_{mc}), P_{600}, P_{60}, and $P_{0.2}$ were determined by extrapolating the relation between the active and reactive power (Q_{mc}) (shown in Table 7).

Table 6. Data Binned by Real Power

Power Bin (% of rated power)	Number of 10-Minute Data Points Per Bin	Output Power, Bin-Mean-Value (kW)	Reactive Power, Bin-Mean-Value (kVAR)
-5 to 5	140	30.25	-2.44
5 to 15	149	143.33	-1.53
15 to 25	92	301.61	-2.59
25 to 35	66	452.99	-3.78
35 to 45	36	600.72	-4.78
45 to 55	46	766.90	-6.20
55 to 65	29	899.74	-7.12
65 to 75	40	1,043.41	-8.07
75 to 85	51	1,206.13	-9.41
85 to 95	45	1,352.76	-10.51
95 to 105	35	1,458.81	-11.22
105 to 115	0	0.00	0.00

Table 7. Maximum Instantaneous Real and Reactive Power

Max. Permitted Power, P_{mc}		**600-Sec Average**		**60-Sec Average**		**0.2-Sec Average**	
P_{mc}, kW ***1,545***	$p_{mc}=P_{mc}/P_n$ ***1.03***	P_{mc}, kW ***1,497.69***	$p_{mc}=P_{mc}/P_n$ ***0.998***	P_{60}, kW ***1,628.34***	$p_{60}=P_{60}/P_n$ ***1.09***	$P_{0.2}$, kW ***1,877.57***	$p_{0.2}=P_{0.2}/P_n$ ***1.25***
Q_{mc} at P_{mc}, kVAR ***-11.74***	$q_{mc}=Q_{mc}/P_n$ ***-0.01***	Q_{mc} at P_{mc}, kVAR ***-11.46***	$q_{mc}=Q_{mc}/P_n$ ***-0.01***	Q_{60} at P_{60}, kVAR ***-12.19***	$q_{60}=Q_{60}/P_n$ ***-0.01***	$Q_{0.2}$ at $P_{0.2}$, kVAR ***-13.23***	$q_{0.2}=Q_{0.2}/P_n$ ***-0.01***

Notes: Data were not normalized to sea-level density. NREL's site average air density is 1.0 kg/m^{3}The active power curve shown in Figure 3 could not be used for the DOE 1.5 power performance evaluation. The official power curve will be published in the DOE 1.5 power performance test report.

5.2 Line Voltage Distortions

The average voltage total harmonic distortions (THD) calculated during the continuous operation test for each phase were:

- Phase A – 1.202%
- Phase B – 1.186%
- Phase C – 1.162%.

The maximum voltage THDs calculated during the test for each phase were:

- Phase A – 1.870%
- Phase B – 1.828%
- Phase C – 1.863%.

Prior to starting the test we verified that the grid voltage THD conditions were less than 5% at the voltage terminals, whereas the turbine was not generating. All voltage THDs were calculated from collected harmonic voltage time series data. The harmonic voltages were subgrouped according to Section 5.6 of IEC 61000-4-7/CDV: General Guide on Harmonics and Interharmonics Measurements and Instrumentation [2]. The window width used during measurements was $T_w=12$.

5.3 Current Harmonics

The individual current harmonics were measured during continuous operation. From these, 10-minute statistics were calculated for each harmonic order (up to 50th) at the given output power, finally determining the maximum individual current harmonic. Table 8 shows the harmonic data and the maximum current total demand distortion (TDD) values as a percentage of nominal current (I_n). Figure 7 shows 10-minute average data for maximum current TDD (% of I_n) of the three phases as a function of output power. The IEEE 519-1992: Harmonic Limits [3] sets a 5% limit on current TDD for all power generation equipment.

Table 8. Maximum Current Harmonics (10-Minute Averages)

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 (%)
1	4.77	12.58	21.00	29.17	37.18	45.18	53.79	60.85	69.69	77.51	81.65
2	0.11	0.12	0.11	0.14	0.15	0.14	0.16	0.16	0.18	0.18	0.19
3	0.72	0.70	0.63	0.62	0.62	0.60	0.64	0.65	0.66	0.65	0.64
4	0.14	0.16	0.14	0.15	0.16	0.17	0.18	0.18	0.18	0.17	0.19
5	2.04	2.19	1.77	1.70	1.64	1.77	1.89	1.68	1.85	1.66	1.66
6	0.12	0.14	0.15	0.17	0.17	0.18	0.19	0.20	0.23	0.24	0.26
7	1.52	1.74	1.82	1.84	1.81	1.35	2.05	1.44	1.90	1.46	1.48
8	0.12	0.13	0.14	0.14	0.15	0.11	0.16	0.12	0.15	0.13	0.14
9	0.13	0.15	0.15	0.14	0.14	0.13	0.14	0.13	0.14	0.15	0.15
10	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09
11	0.27	0.34	0.37	0.43	0.43	0.47	0.51	0.47	0.47	0.47	0.46
12	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
13	0.10	0.12	0.14	0.17	0.25	0.26	0.27	0.32	0.31	0.32	0.35
14	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06
15	0.08	0.08	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07
16	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.08	0.08	0.08
17	0.24	0.26	0.24	0.24	0.25	0.20	0.20	0.20	0.18	0.18	0.23
18	0.14	0.16	0.14	0.14	0.14	0.15	0.14	0.15	0.14	0.14	0.14
19	0.33	0.35	0.30	0.30	0.27	0.25	0.25	0.26	0.25	0.27	0.30
20	0.17	0.22	0.19	0.19	0.20	0.21	0.20	0.21	0.21	0.21	0.21
21	0.17	0.24	0.19	0.20	0.20	0.22	0.21	0.22	0.22	0.22	0.22
22	0.17	0.23	0.20	0.19	0.20	0.20	0.20	0.21	0.21	0.22	0.22
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 (%)
23	0.55	0.62	0.63	0.63	0.63	0.67	0.68	0.71	0.71	0.75	0.74
24	0.13	0.16	0.14	0.14	0.14	0.14	0.14	0.15	0.15	0.16	0.16
25	0.22	0.26	0.23	0.22	0.22	0.20	0.18	0.18	0.16	0.17	0.16
26	0.09	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
27	0.08	0.10	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
28	0.08	0.09	0.09	0.09	0.08	0.09	0.08	0.09	0.09	0.09	0.09
29	0.11	0.16	0.15	0.16	0.21	0.22	0.23	0.27	0.27	0.27	0.28
30	0.19	0.19	0.11	0.12	0.10	0.10	0.11	0.11	0.13	0.12	0.14
31	0.07	0.10	0.08	0.09	0.09	0.07	0.08	0.08	0.07	0.08	0.08
32	0.24	0.25	0.13	0.12	0.08	0.07	0.07	0.07	0.07	0.07	0.08
33	0.05	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.06
34	0.04	0.04	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04
35	0.09	0.09	0.10	0.10	0.09	0.08	0.08	0.08	0.07	0.07	0.08
36	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
37	0.05	0.04	0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.04
38	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
39	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
40	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
41	0.03	0.04	0.04	0.04	0.04	0.05	0.04	0.05	0.05	0.05	0.04
42	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
43	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
44	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
45	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
46	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
47	0.01	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.01	0.01
48	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
49	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
50	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
THC (%)	0.35	0.91	1.51	2.09	2.67	3.24	3.86	4.37	5.00	5.56	5.86

Max. phase A current TDD (% of I_n)	***2.82***	**Output power at max. current THD (kW)**	**866.83**
Max. phase B current TDD (% of I_n)	***2.67***	**Output power at max. current THD (kW)**	**866.83**
Max. phase C current TDD (% of I_n)	***2.70***	**Output power at max. current THD (kW)**	**866.83**

The current harmonics were subgrouped according to Section 5.6 of IEC 61000-4-7/CDV [2] as prescribed in the Standard. The window width used during measurements was $T_w=12$.

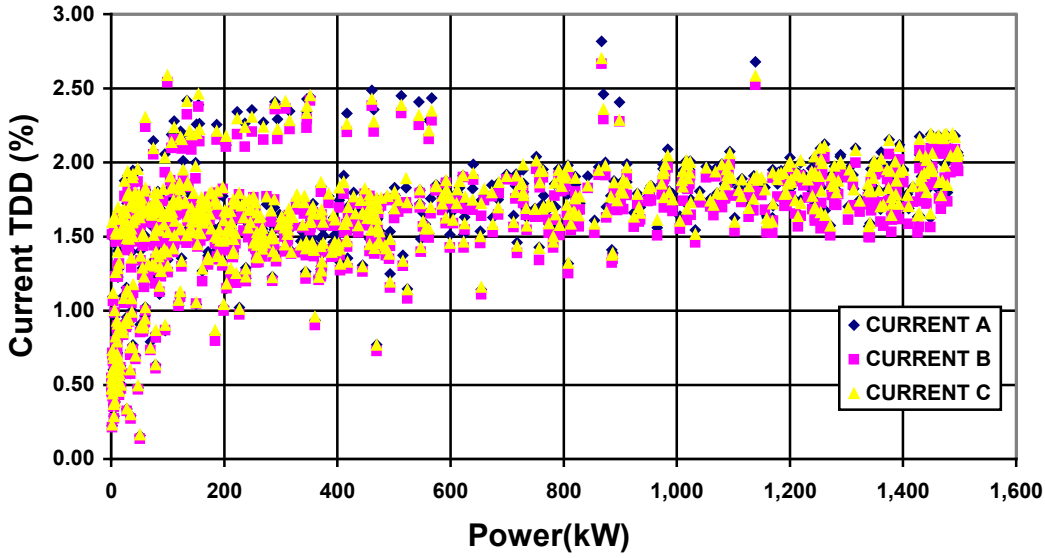


Figure 7. Current TDD versus active power

5.4 Current Interharmonics

Table 9 lists the maximum 10-minute average for each individual interharmonic current below 2 kHz as a percentage of nominal current (I_n).

Table 9. Current Interharmonics

f	0	10	20	30	40	50	60	70	80	90	100
(Hz)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)	I_h (%)
90	0.14	0.16	0.20	0.25	0.24	0.32	0.37	0.44	0.33	0.47	0.40
150	0.20	0.23	0.22	0.23	0.31	0.33	0.35	0.36	0.36	0.38	0.40
210	0.24	0.29	0.28	0.35	0.36	0.36	0.36	0.36	0.34	0.32	0.32
270	0.19	0.23	0.24	0.25	0.31	0.28	0.28	0.36	0.31	0.43	0.58
330	0.22	0.26	0.27	0.31	0.32	0.31	0.31	0.30	0.29	0.30	0.29
390	0.23	0.26	0.28	0.30	0.33	0.35	0.39	0.41	0.46	0.48	0.51
450	0.22	0.25	0.27	0.28	0.28	0.21	0.29	0.20	0.29	0.20	0.21
510	0.19	0.20	0.22	0.23	0.24	0.20	0.28	0.23	0.30	0.25	0.25
570	0.15	0.15	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.17
630	0.13	0.14	0.15	0.15	0.15	0.15	0.15	0.16	0.16	0.16	0.16
690	0.13	0.14	0.14	0.14	0.14	0.15	0.15	0.15	0.15	0.15	0.15
750	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.14
810	0.12	0.12	0.13	0.13	0.12	0.12	0.12	0.12	0.12	0.12	0.12
870	0.12	0.12	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.12	0.12
930	0.14	0.14	0.15	0.15	0.14	0.14	0.14	0.14	0.13	0.13	0.13
990	0.17	0.20	0.19	0.18	0.18	0.17	0.17	0.17	0.17	0.16	0.17
1050	0.22	0.26	0.23	0.22	0.22	0.23	0.22	0.23	0.22	0.22	0.22
1110	0.26	0.33	0.27	0.27	0.28	0.30	0.29	0.30	0.29	0.30	0.29
1170	0.28	0.37	0.31	0.32	0.33	0.35	0.34	0.35	0.34	0.35	0.35
1230	0.29	0.40	0.33	0.34	0.35	0.37	0.37	0.39	0.38	0.38	0.39
1290	0.30	0.42	0.35	0.35	0.37	0.38	0.38	0.39	0.40	0.40	0.40
1350	0.29	0.38	0.34	0.33	0.36	0.34	0.35	0.37	0.36	0.37	0.37
1410	0.25	0.32	0.28	0.28	0.29	0.30	0.29	0.33	0.31	0.32	0.32
1470	0.20	0.25	0.22	0.23	0.23	0.22	0.23	0.23	0.23	0.23	0.25
1530	0.17	0.20	0.18	0.19	0.18	0.17	0.17	0.17	0.17	0.17	0.19
1590	0.14	0.18	0.15	0.15	0.15	0.16	0.15	0.16	0.16	0.16	0.16
1650	0.14	0.17	0.16	0.16	0.15	0.16	0.15	0.17	0.17	0.17	0.17
1710	0.14	0.17	0.15	0.15	0.14	0.15	0.15	0.15	0.15	0.15	0.15
1770	0.13	0.16	0.14	0.14	0.13	0.13	0.14	0.14	0.14	0.14	0.14
1830	0.12	0.15	0.14	0.15	0.17	0.17	0.17	0.17	0.17	0.18	0.17
1890	0.25	0.26	0.18	0.17	0.15	0.13	0.14	0.13	0.14	0.14	0.15
1950	0.10	0.12	0.11	0.11	0.11	0.11	0.11	0.10	0.11	0.11	0.11
2010	0.15	0.15	0.11	0.12	0.12	0.13	0.13	0.14	0.14	0.15	0.15
2070	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.07	0.07
2130	0.05	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
2190	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
2250	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06
2310	0.03	0.04	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04
2370	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
2430	0.02	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
2490	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03
2550	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
2610	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
2670	0.02	0.08	0.08	0.08	0.08	0.08	0.06	0.07	0.07	0.04	0.03
2730	0.31	0.31	0.31	0.31	0.31	0.32	0.32	0.31	0.31	0.31	0.31
2790	0.02	0.09	0.09	0.09	0.09	0.09	0.07	0.09	0.09	0.04	0.02
2850	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
2910	0.01	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02
2970	0.24	0.24	0.24	0.24	0.24	0.24	0.25	0.24	0.24	0.24	0.24
3030	0.02	0.07	0.07	0.07	0.07	0.07	0.05	0.06	0.06	0.03	0.02

The current interharmonics were subgrouped according to Annex A of IEC 61000-4-7/CDV: General Guide on Harmonics and Interharmonics Measurements and Instrumentation [2], as prescribed in the Standard. The window width used during measurements was $T_w=12$.

5.5 Current Distortions

Table 10 lists the maximum 10-minute average current distortions in the range of 2 kHz up to 9 kHz as a percentage of nominal current (I_n).

Table 10. Current Distortions (2–9 kHz)

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	0.19	0.19	0.17	0.17	0.15	0.14	0.15	0.15	0.15	0.16	0.17
2.3	0.11	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
2.5	0.06	0.06	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
2.7	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
2.9	0.24	0.25	0.25	0.26	0.26	0.26	0.25	0.26	0.26	0.25	0.24
3.1	0.16	0.17	0.17	0.17	0.17	0.17	0.16	0.17	0.17	0.16	0.15
3.3	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
3.5	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.02	0.03	0.02	0.02
3.7	0.04	0.05	0.05	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07
3.9	0.04	0.06	0.05	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.07
4.1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
4.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4.5	0.08	0.09	0.06	0.07	0.08	0.07	0.08	0.07	0.06	0.08	0.08
4.7	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
4.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
5.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
5.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
5.5	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
5.7	0.05	0.06	0.05	0.05	0.05	0.05	0.05	0.06	0.05	0.05	0.05
5.9	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
6.1	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05
6.3	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6.7	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
6.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
7.1	0.00	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
7.3	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
7.5	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
7.7	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
7.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8.1	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8.3	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
8.5	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
8.7	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01
8.9	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01

The current distortions were measured and evaluated according to Annex B of IEC 61000-4-7/CDV [2], as prescribed in the Standard. The window width used during measurements was $T_w=12$.

5.6 Current and Voltage Imbalance

Figure 8 and Figure 9 show the voltage and current imbalance observed during the testing. The current and voltage imbalance was calculated for each 10-minute period. The values are plotted against the average power of each 10-minute data set.

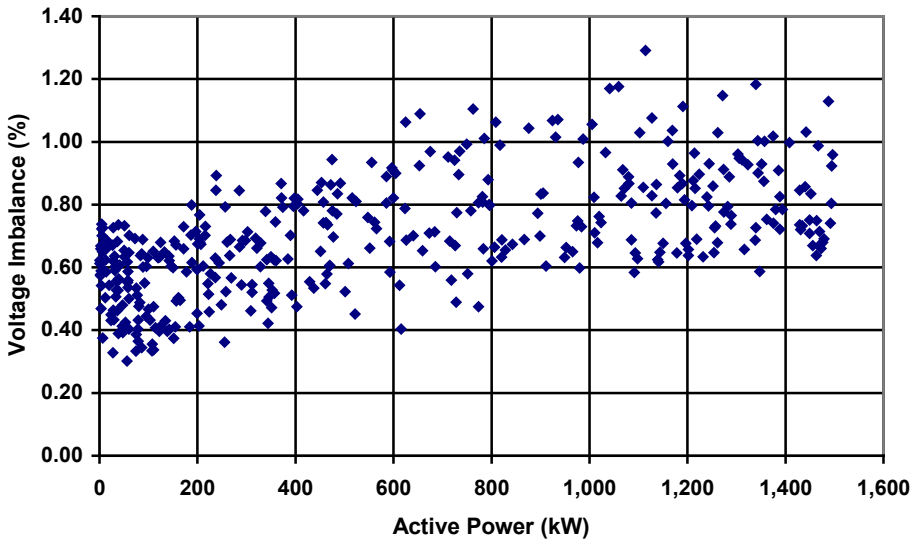


Figure 8. Voltage imbalance versus active power

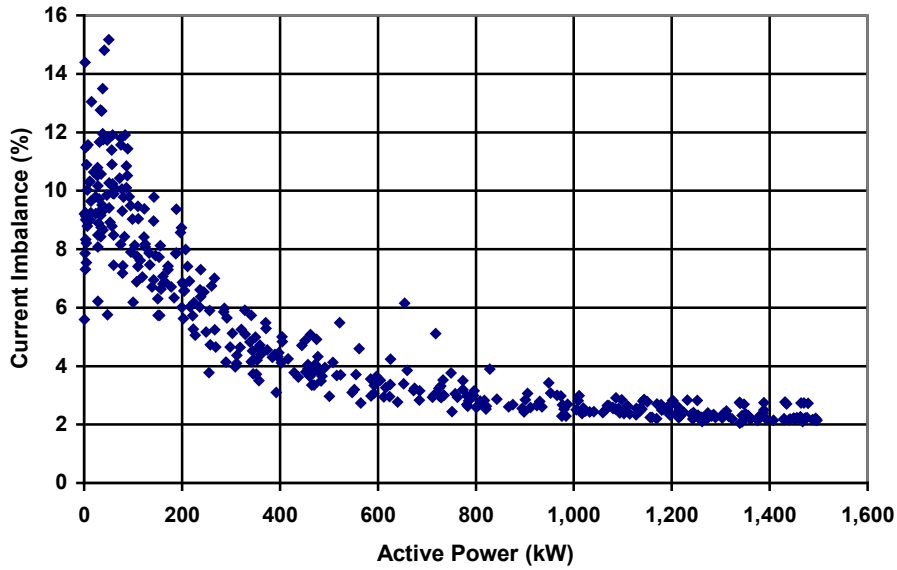


Figure 9. Current imbalance versus active power

5.7 Continuous Operation Flicker

The flicker coefficients $c(\Psi_k, V_a)$ were determined according to procedures listed in the Standard. A total of 730 10-minute interval data bins were collected for this test.

Figure 10 through Figure –13 show graphs of fictitious grid flicker coefficients as a function of 10-minute average active power for four different impedance phase angles (30°, 50°, 70°, and 85°). Resulting flicker coefficients for continuous operation are shown in Table 11. The ratio between three-phase short circuit apparent power of the fictitious grid $S_{k,fic}$ and turbine rated apparent power S_n used for the analysis was 50.

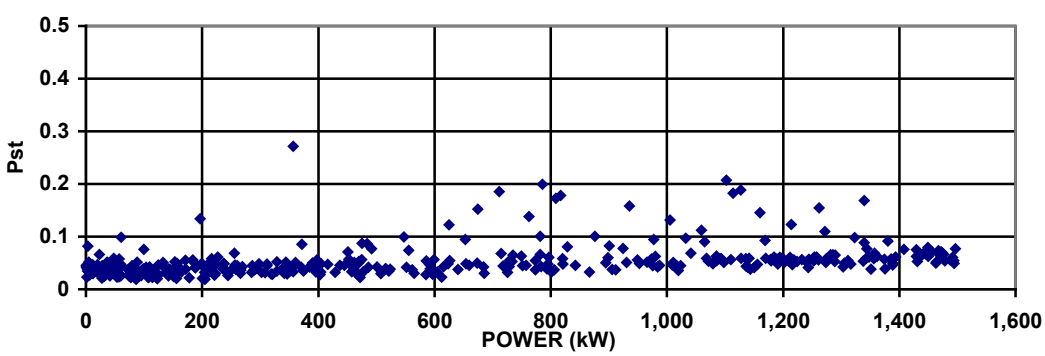


Figure 10. Short-term flicker (P_{st}) versus power for 30° network impedance angle

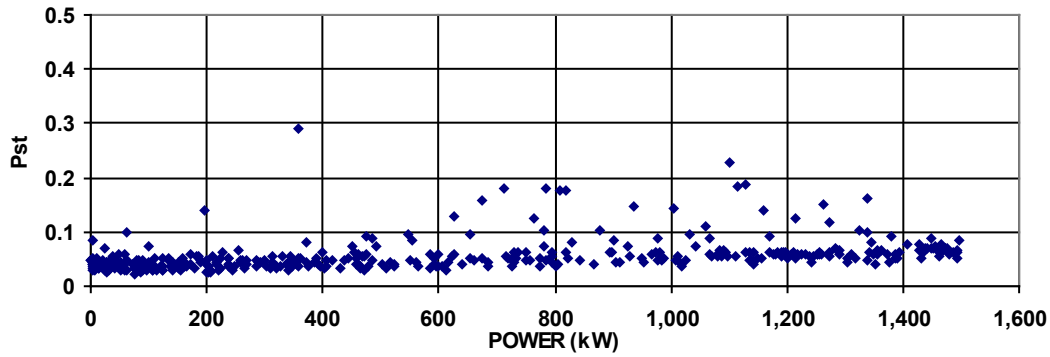


Figure 11. Short-term flicker (P_{st}) versus power for 50° network impedance angle

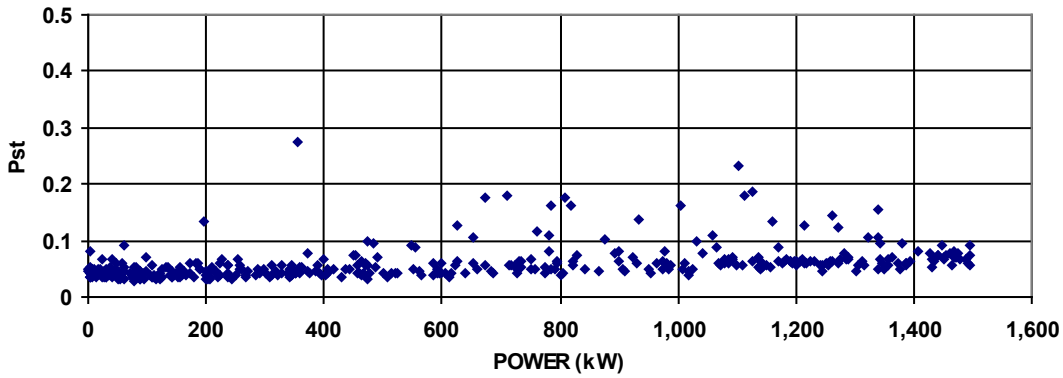


Figure 12. Short-term flicker (P_{st}) versus power for 70° network impedance angle

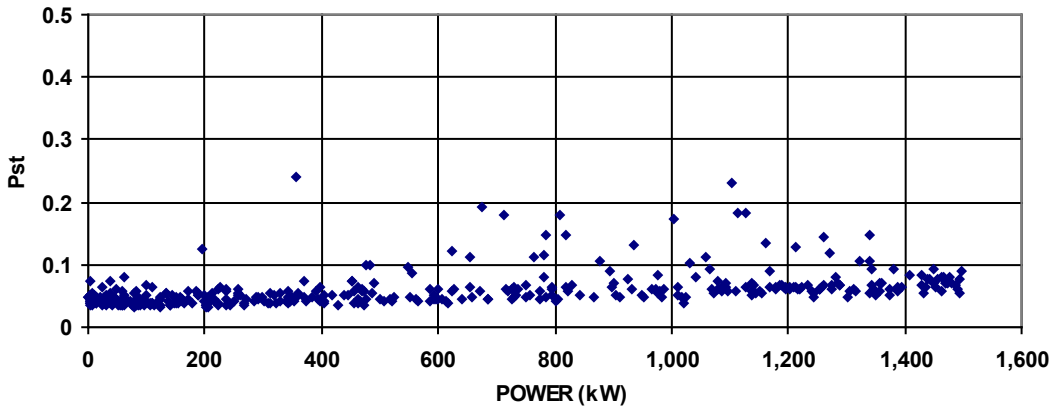


Figure 13. Short-term flicker (P_{st}) versus power for 85° network impedance angle

The simulated flicker values P_{st} depend on short-circuit apparent power of the fictitious grid $(S_{k,fic})$ and the grid impedance angle. To reduce this dependency, the Standard defines a flicker coefficient $c(\Psi_k, V_a)$, which is calculated as a normalized quantity according to the Standard, where Ψ_k is the network impedance phase angle and V_a is the

annual average wind speed. Table 11shows the flicker coefficient of the wind turbine for the actual Ψ_k and V_a at the site, as calculated by applying linear interpolation.

Table 11. Resulting Flicker Coefficients $c(\Psi_k, V_a)$ in Continuous Operation

Network impedance phase angle, Ψ_k (deg):	**30°**	**50°**	**70°**	**85°**
Annual average wind speed, V_a (m/s):	Flicker coefficients, $c(\Psi_k, V_a)$:			
6	7.43	7.57	7.78	7.45
7.5	7.43	7.57	7.78	7.45
8.5	7.43	7.57	7.78	7.45
10	7.43	7.57	7.78	7.45

6 Switching Operation Test Results

6.1 Turbine Starts and Stops

Normal start and stop tests were conducted at cut-in and rated wind speeds. The hub-height meteorological tower wind speed was recorded during the tests along with voltage and current waveforms. The resulting 10-minute average wind speed during the switching operation was within ±2 m/s of the required test wind speed. The measurements were taken for a long enough period to ensure that the transient of the switching operation had abated but not so long as to introduce possible power fluctuations due to turbulence. The switching operation measurements ranged from 30 seconds to 2 minutes.

Figure 14 through Figure 21 show the transients for the start and stop cases for active power, reactive power, and current. The time series RMS voltages for Phase A are also shown for each case to illustrate voltage fluctuations during switching operations.

The voltage and current time series were combined as prescribed by the Standard to simulate a fictitious voltage time series $u_{fic}(t)$ for four different network impedance angles. The flicker step factors and voltage change factors were determined for each switching operation for four impedance angles (Table 12 through –Table 15).

Cut-in start waveforms are shown in Figure 14 and Figure 15. Rated start waveforms are shown in Figure 16 and Figure 17.

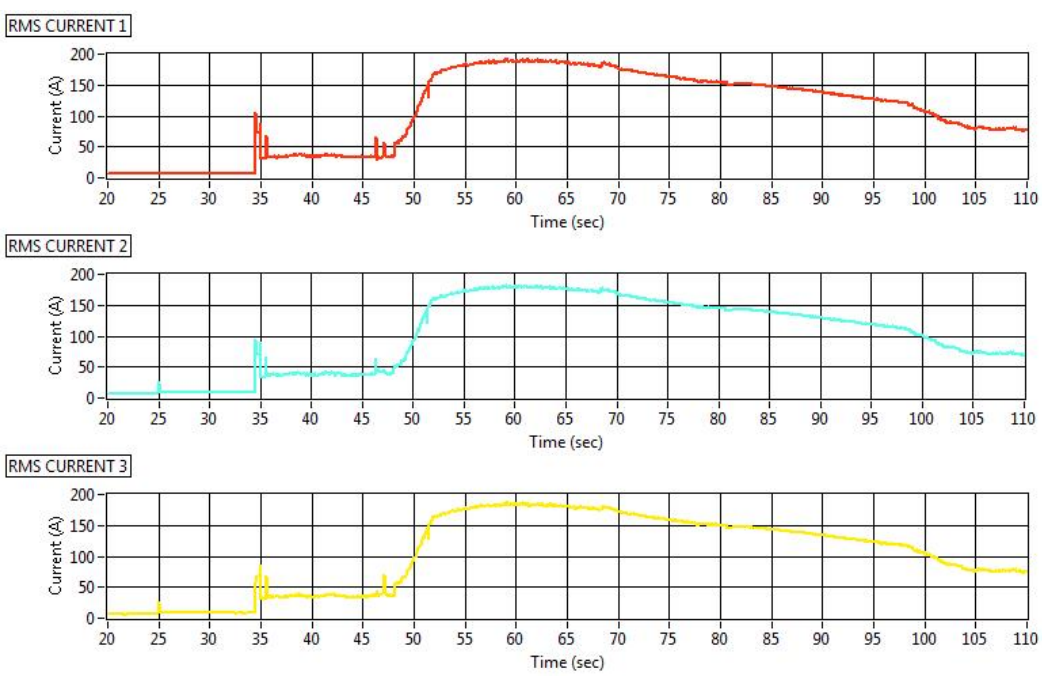


Figure 14. Cut-in wind (5.3 m/s) start: current (May 18, 2011)

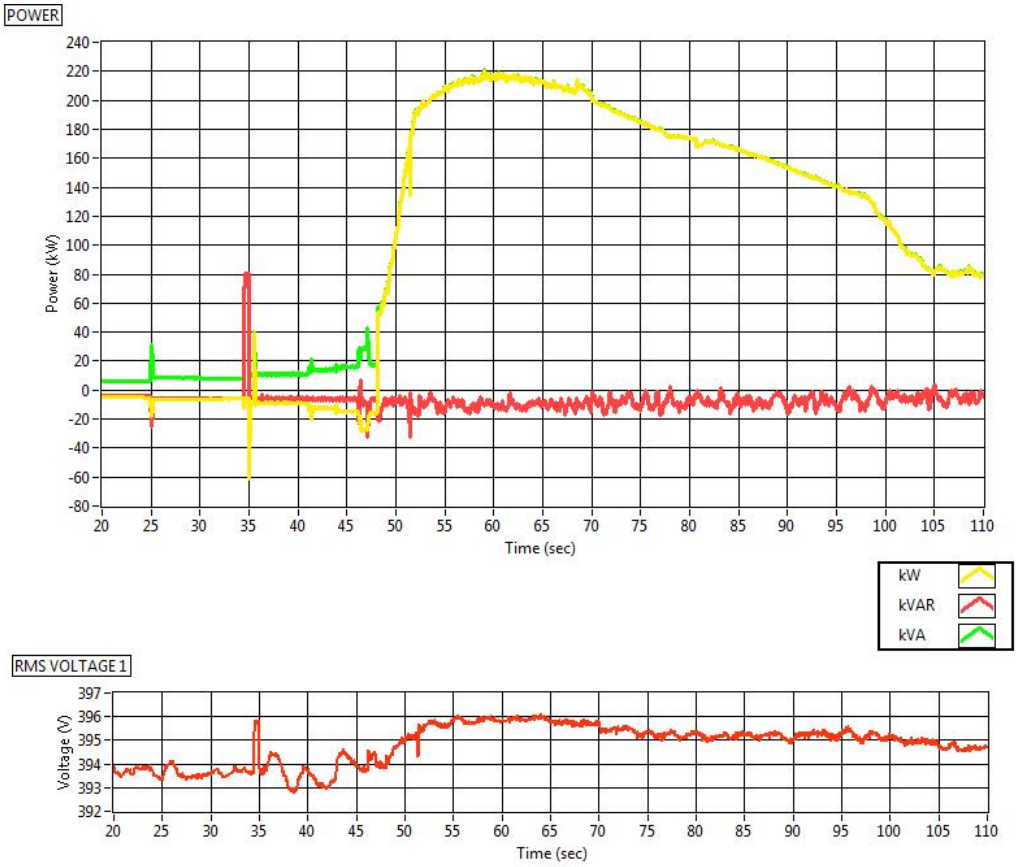


Figure 15. Cut-in wind (5.3 m/s) start: power and RMS voltage (May 18, 2011)

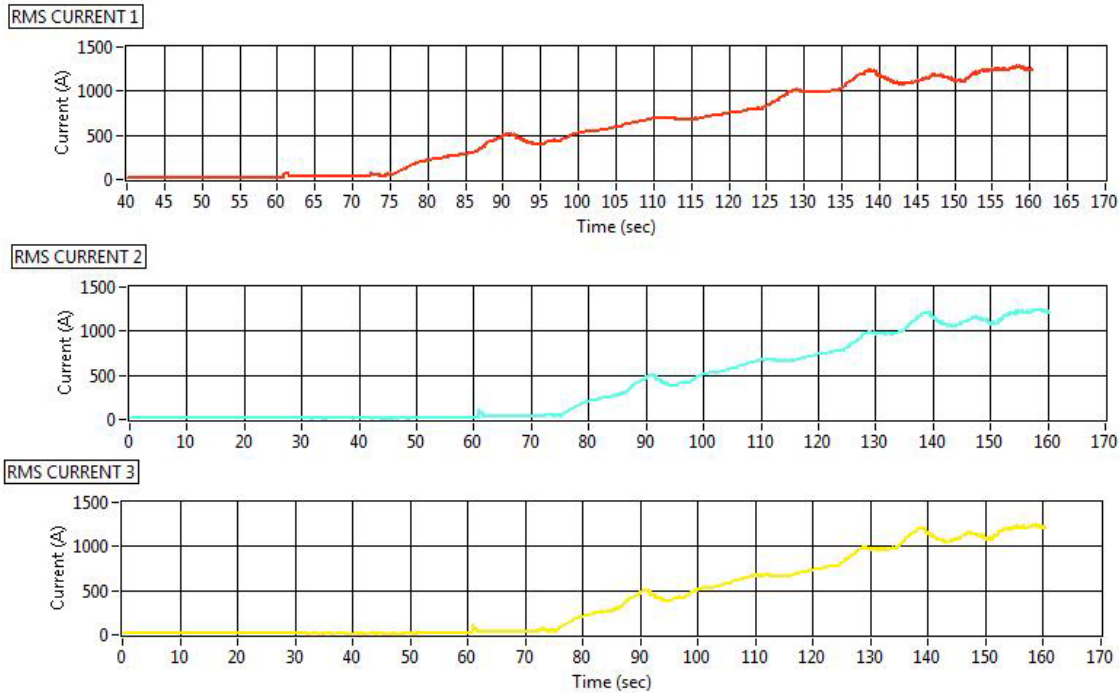


Figure 16. Rated wind (13.1 m/s) start: current (April 19, 2011)

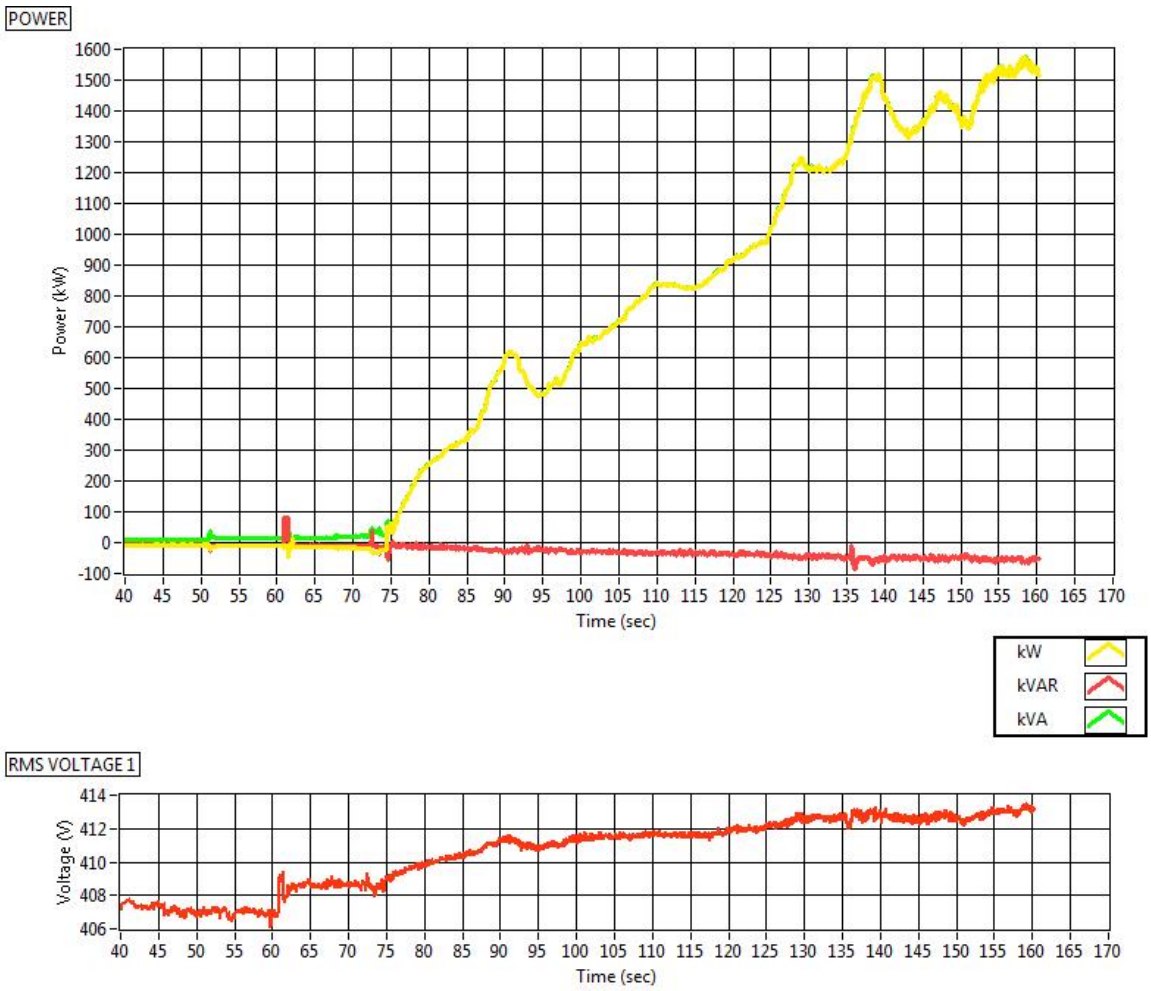


Figure 17. Rated wind (13.1 m/s) start: power and RMS voltage (April 19, 2011)

Cut-in stop waveforms are shown in Figure 18 and Figure 19. Rated stop waveforms are shown in Figure 20 and Figure 21.

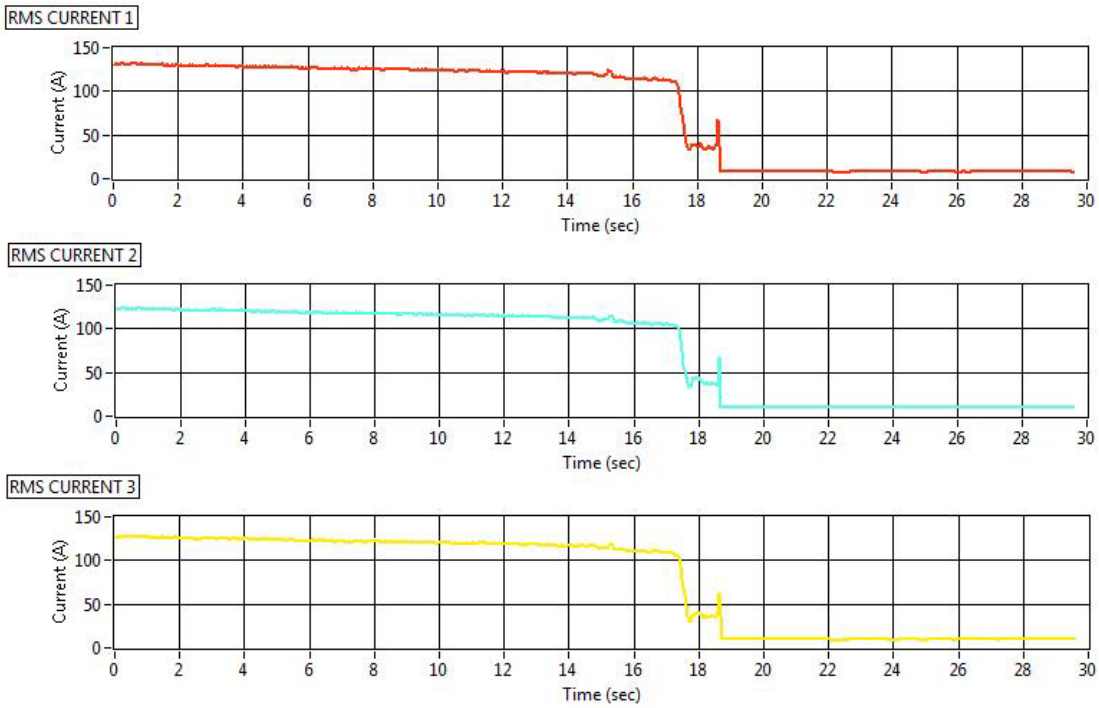


Figure 18. Cut-in wind (5.0 m/s) stop: current (May 18, 2011)

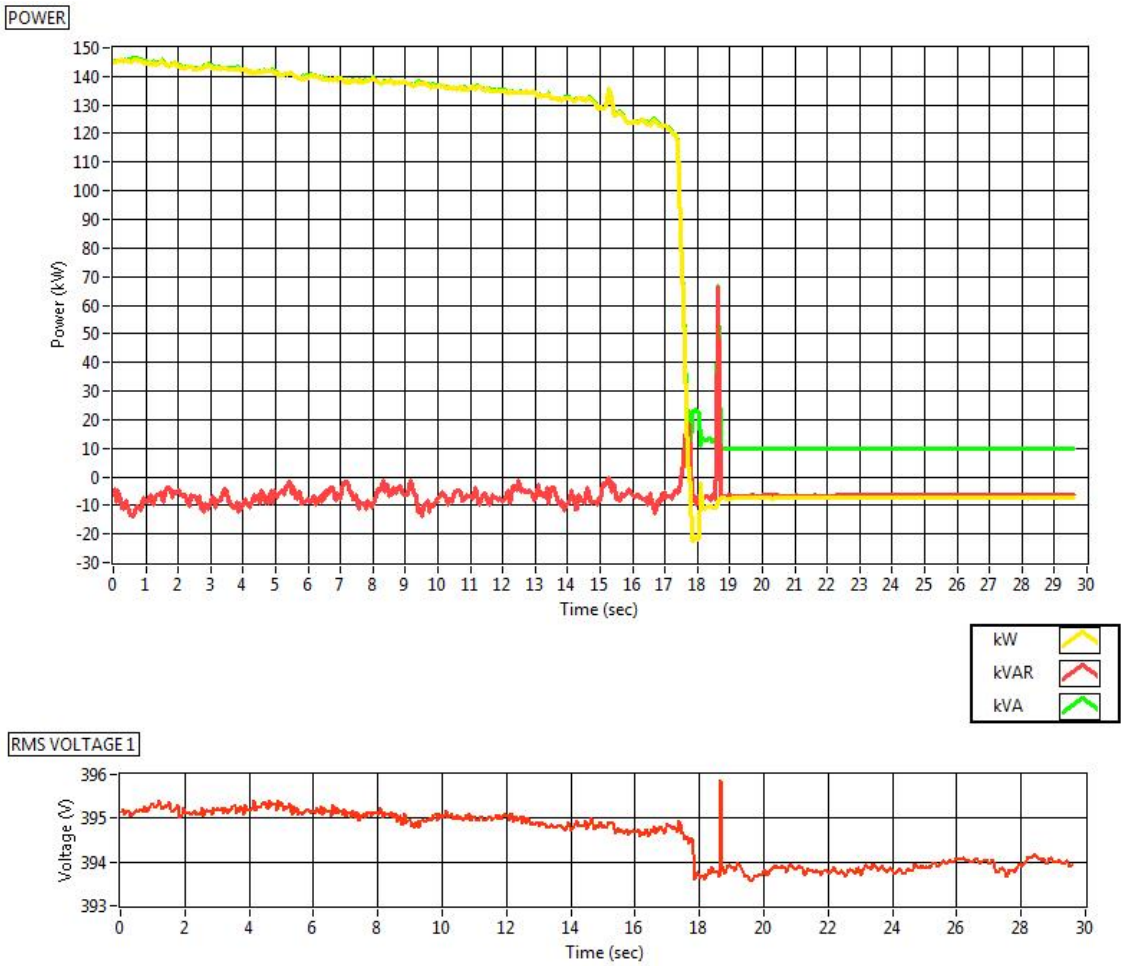


Figure 19. Cut-in wind (5.0 m/s) stop: power and RMS voltage (May 18, 2011)

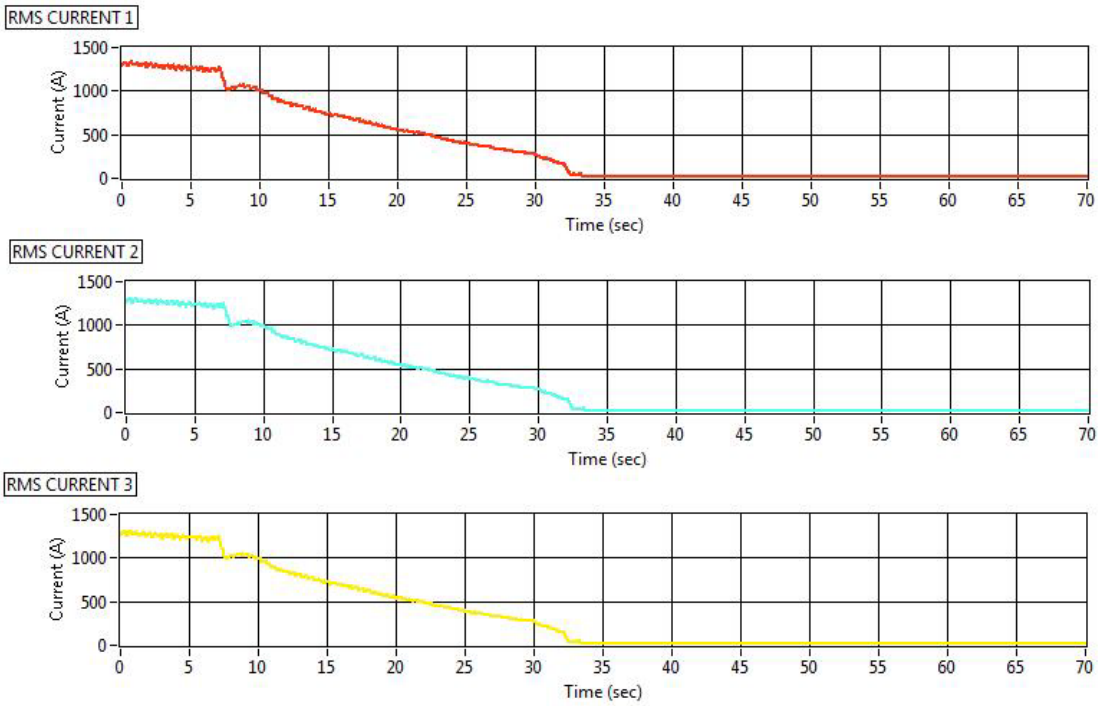


Figure 20. Rated wind (13.8 m/s) stop: current (April 19, 2011)

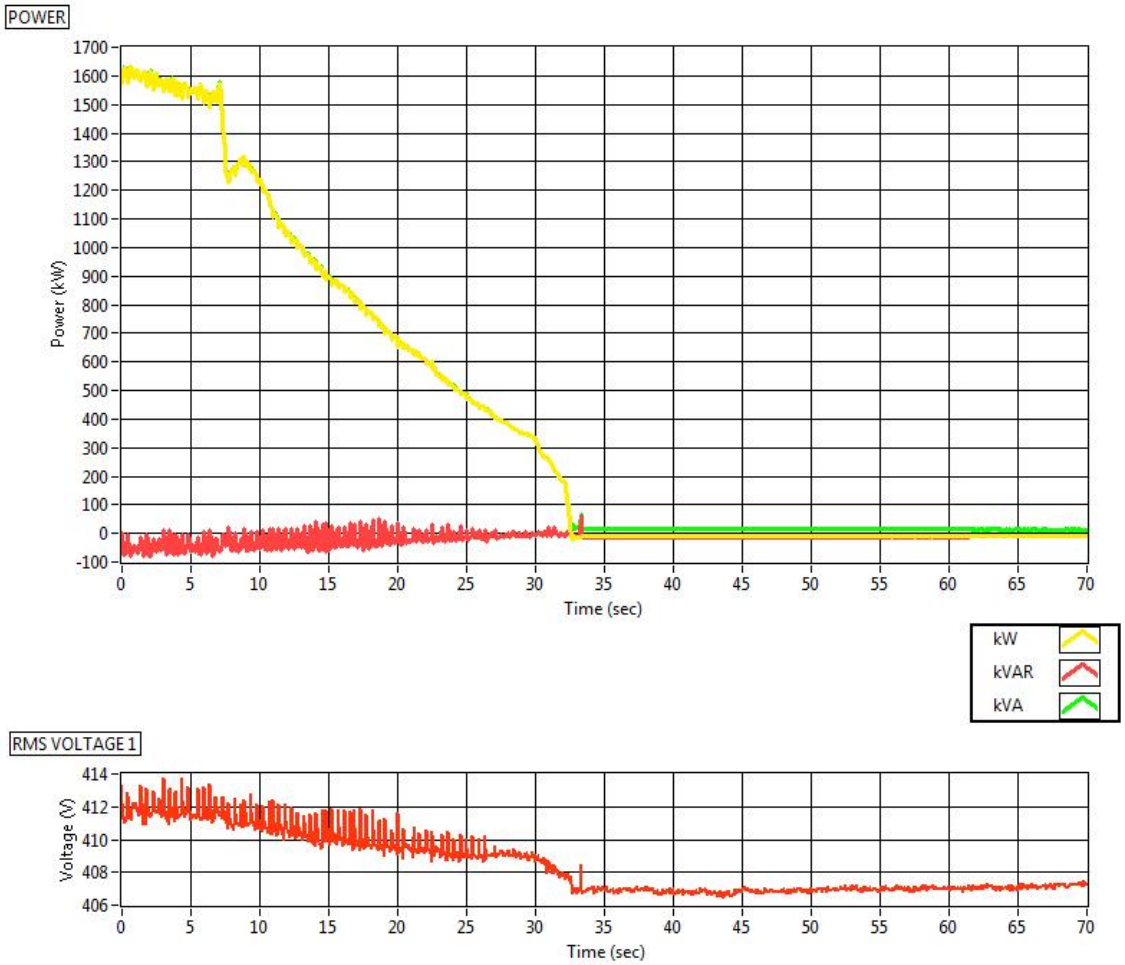


Figure 21. Rated wind (13.8 m/s) stop: power and RMS voltage (April 19, 2011)

The maximum number of switching operations for 10-minute and 120-minute intervals (N_{10m} and N_{120m}) was 10 and 120 for cut-in and 1 and 1 for rated wind speeds, respectively. The N_{10} and N_{120} values were assumed based on the procedure defined by the Standard. The flicker step factor and voltage change factors were the averaged result of five starts and stops at cut-in and rated wind speeds. These values are shown in Table 12 through Table15.

Table 12. Characteristics of a Start at Cut-In Wind Speed

Case of switching operation	*Start at cut-in wind speed*			
Maximum number of switching operations, N_{10m}	10			
Maximum number of switching operations, N_{120m}	120			
Network impedance angle, Ψ_k	*30°*	*50°*	*70°*	*85°*
Flicker step factor, $k_f(\Psi_k)$	0.015	0.015	0.015	0.015
Voltage change factor, $k_U(\Psi_k)$	0.028	0.036	0.042	0.043

Table 13. Characteristics of a Stop at Cut-In Wind Speed

Case of switching operation	***Stop at cut-in wind speed***			
Maximum number of switching operations, $N_{10:m}$	10			
Maximum number of switching operations, N_{120m}	120			
Network impedance angle, $\Psi_{k:}$	*30°*	*50°*	*70°*	*85°*
Flicker step factor, $k_f(\Psi_k)$:	0.095	0.116	0.132	0.140
Voltage change factor, $k_U(\Psi_k)$:	0.017	0.017	0.017	0.017

Table 14. Characteristics of a Start at Rated Wind Speed

Case of switching operation:	***Start at rated wind speed***			
Maximum number of switching operations, $N_{10m:}$	1			
Maximum number of switching operations, $N_{120m:}$	12			
Network impedance angle, $\Psi_{k:}$	*30°*	*50°*	*70°*	*85°*
Flicker step factor, $k_f(\Psi_k)$:	0.000	0.000	0.000	0.000
Voltage change factor, $k_U(\Psi_k)$:	0.030	0.039	0.046	0.048

Table 15. Characteristics of a Stop at Rated Wind Speed

Case of switching operation:	***Stop at rated wind speed***			
Maximum number of switching operations, $N_{10m:}$	1			
Maximum number of switching operations, $N_{120m:}$	12			
Network impedance angle, $\Psi_{k:}$	*30°*	*50°*	*70°*	*85°*
Flicker step factor, $k_f(\Psi_k)$:	0.000	0.000	0.000	0.000
Voltage change factor, $k_U(\Psi_k)$:	0.011	0.011	0.011	0.011

The flicker step factor and voltage change factor of the wind turbine for the actual Ψ_k at the site can be found from the tables above by applying linear interpolation.

7 Uncertainty

The data acquisition system (DAS) consists of:

- National Instrument's cDAQ-9172
- Two NI 9239 24-bit modules with four analog inputs
    - Serial numbers:14D84D5, 14D84FE
- Three LEM CV3-1200 voltage transformers
    - Serial numbers: 947323,947325, 947322
- Three LEMflex RR3035 current transformers
    - Serial numbers: F06110402818, F06110403118, F05461044218
- One Thies Clima 4.3351.10.0000
    - Serial Number: 0909219
- LabVIEW software developed by NREL, Version 6.10
- Max sampling rate 25 kHz for continuous operation
- Max sampling rate 5 kHz for transients

The uncertainty of the measuring system is given in Table 16.

Table 16. Uncertainty Analysis of the Measuring System

Measured Value	Gain Error	Offset Error	Overall Uncertainty of the Measured Value
Active and reactive power	A/D 0.13% Current transformer 1.0% Voltage transformer 0.2%	A/D 0.06%	Active power: 1.6% Reactive power: 1.6%
Harmonic current (Sampling rate 25 kHz)	Harmonics up to 9 kHz Bandwidth 5 Hz 1.4% of measured value	Harmonics up to 9 kHz Bandwidth 5 Hz 0.06% of rated current	0.06% of rated current + 1.4% of measured value

8 Exceptions

8.1 Exceptions to the Standard

There were two identified exceptions to the Standard. The response to temporary voltage drop test and the grid protection test that are required by the second edition were not performed because the necessary test assets were not available in North America.

Also, because the necessary technical information was confidential and not available from the manufacturer, the following tests were excluded from this testing campaign:

- Power control
- Voltage drop response
- Grid connection and reconnection.

8.2 Exceptions to the Test Plan

There were no deviations from the test plan [4].

References

1. International Electrotechnical Commission (IEC). (2008). “Wind Turbines, Part 21: Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines.” IEC 61400-21. Edition 2.0, 2008-08. Geneva, Switzerland.
2. IEC. (2002). “IEC 61000-4-7 Testing and Measurement Techniques – General Guide on Harmonics and Interharmonics Measurements and Instrumentation, for Power Supply Systems and Equipment Connected Thereto.” Geneva, Switzerland.
3. Institute of Electrical and Electronics Engineers. (1993). “IEEE 519-1992: IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.” New York, New York.
4. QF02 Power Quality Test Plan DOE 1.5 101006

Appendix A. Calibration Reports

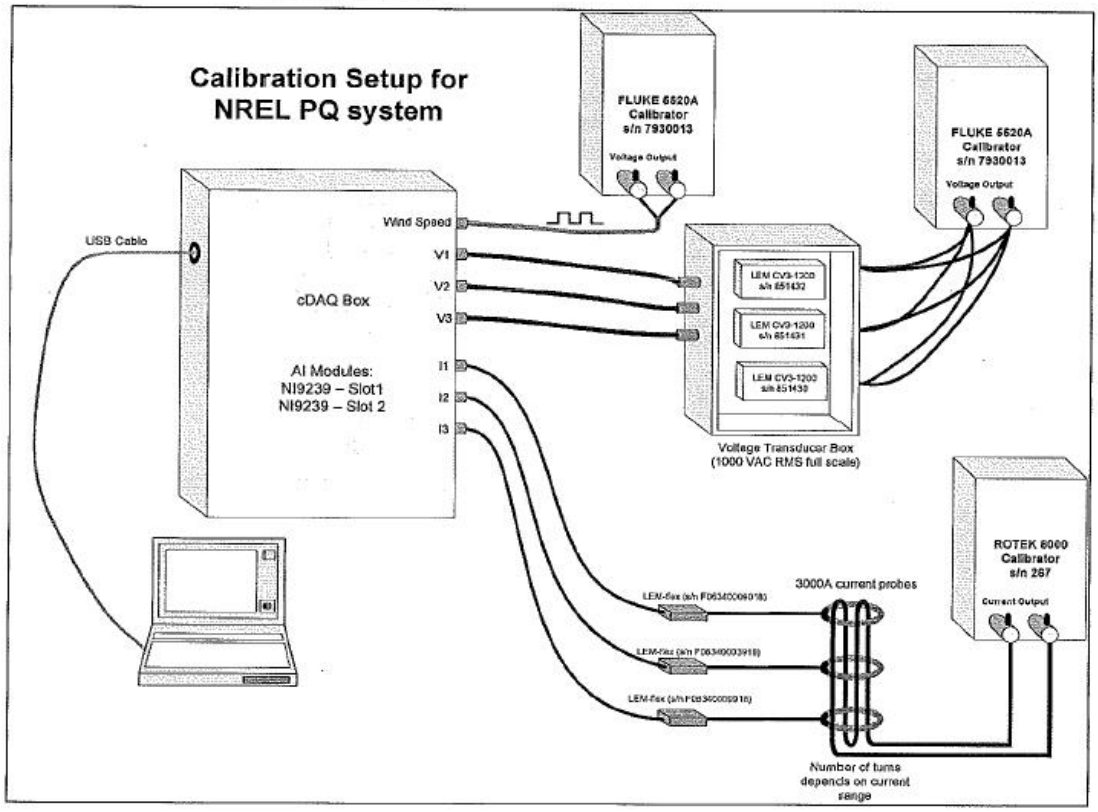
Power

NREL
National Renewable Energy Laboratory

Calibration Report

Report #: NREL PQ Sampling System Cal (sn PQ05) 100813

Calibration of: NREL PQ Sampling System



Environmental Conditions During Calibration

Temperature:	23C, +/- 1C
Relative humidity:	40%, +/-10%

Calibration Method:	GI28 010717
Calibration Results:	Within tolerance
Device Condition:	good
Date Calibrated:	8/12/2010
Calibration Due Date:	8/12/2011
Calibrated by:	Amy, Ismael, and Reda
NREL Metrology Laboratory:	Ibrahim Reda Senior Scientist-II Date: 8/17/2010

8/17/2010 PQ Sampling System Cal Report (sn PQ05) 100413 20100812 (version 1).xlsx Page 1 of 6

Figure A-1. Calibration sheet for the power transducer (page 1)

Calibration Standard:

Rotek Current Calibrator

Model:	8000A	Calibration Date:	7/8/2010
Serial # :	267	Calibration Due Date:	7/8/2011
DOE Tag:	126314		

Fluke Voltage Calibrator

Model:	5520A	Calibration Date:	7/29/2010
Serial # :	7930013	Calibration Due Date:	7/29/2011
DOE Tag:	126410		

Accuracy

Current (<50A):	0.036 % of setting	+	0.005 % of range
Current (>50A):	0.05 % of reading	+	0.008 % of range
Voltage:	0.03 % of reading	+	0.01 V

Full Scale Settings

Rotek 8000A Current:	200 A
Fluke 5520A Voltage:	700 V

Unit Under Test (UUT):

Current sensors

Model:	LEM RR3035-24						
Accuracy:	1 % of F.S.						
Full scale:	-3000	3000 A	Output:	-3	to	3	V
			Nominal Slope:		1000		
			Nominal Offset:		0		

Voltage sensors

Model:	LEM CV3-1200		Output:	-10	to	10	V
Accuracy:	0.2 % of F.S.		Nominal Slope:		150.00		
Full scale:	-1500	1500 V	Nominal Offset:		0		

Communication unit

Model: S.I. Tech 2173

Filter cut-off:

A/D Converter

Model: NI-9239

Combined accuracy of A/D Converter: 0.7 % of F.S.

Uncertainty of UUT:

Current Total Uncertainty =	36.62 A
Voltage Total Uncertainty =	10.92 V

Note:

1. The Test Uncertainty Ratio (TUR) = The uncertainty of the unit under test (UUT) divided by the uncertainty of the standard.
2. All uncertainties are calculated using the Volt or Amper values, not percentages.
3. The total uncertainty for the UUT is calculated as the RSS of the uncertainties of the current and voltage sensors, and A/D converter

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Figure A-2. Calibration sheet for the power transducer (page 2)

Current Measurements

ROTEK 8000A	Within	Unit Under Test						
RMS Current	Tolerance?	Phase 1		Phase 2		Phase 3		TUR
A		V	Error, A	V	Error, A	V	Error, A	
0	Yes	0.001	-2.08	0.001	2.72	0.001	2.64	3662
200	Yes	0.203	-0.19	0.203	0.11	0.202	-0.01	447
400	Yes	0.405	1.69	0.406	-1.52	0.404	-1.68	238
600	Yes	0.608	4.58	0.608	-4.12	0.606	-3.35	162
800	Yes	0.802	-1.52	0.818	1.09	0.814	0.87	123
1000	Yes	1.002	-1.64	1.022	0.44	1.017	0.18	99
1200	Yes	1.203	-0.75	1.227	0.77	1.221	0.47	83
1400	Yes	1.403	-0.86	1.431	0.12	1.425	0.77	71
1600	Yes	1.604	0.03	1.636	0.45	1.628	0.08	62
1800	Yes	1.804	-0.08	1.840	-0.20	1.832	0.37	56
2000	Yes	2.005	0.81	2.045	0.13	2.035	-0.32	50

Calculated slope and offset: *TUR is always >4*

Slope:	999.45	977.21	981.83
Offset:	-3.0811999	1.7388932	1.656462

Frequency Measurements

Fluke 5520A	Within	Unit under test	
Frequency	Tolerance?	Wind Speed Input	
Hz		Hz	Error, Hz
100	Yes	100.000	0.02
200	Yes	199.985	0.00
300	Yes	299.943	-0.04
400	Yes	400.000	0.01
500	Yes	500.002	0.01
600	Yes	599.982	-0.01
800	Yes	799.995	0.00
900	Yes	899.998	0.00

Calculated slope and offset:

Slope:	1.00
Offset:	0.01994328

Voltage Measurements

Line-to-neutral or line-to-ground measurements

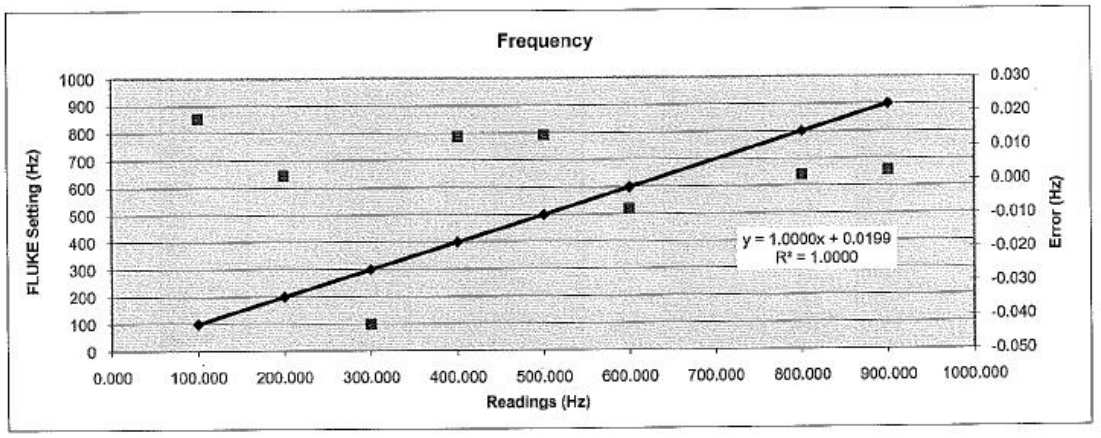
ROTEK 8000A	Within	Unit Under Test						
RMS Voltage	Tolerance?	Phase 1		Phase 2		Phase 3		TUR
V		V	Error, V	V	Error, V	V	Error, V	
640	Yes	4.256	-0.08	4.264	-0.08	4.267	0.01	45
660	Yes	4.389	-0.15	4.398	0.03	4.4	-0.04	44
680	Yes	4.523	-0.07	4.531	-0.01	4.533	-0.09	43
700	Yes	4.656	-0.14	4.664	-0.06	4.667	0.00	42
720	Yes	4.789	-0.22	4.797	-0.10	4.8	-0.05	41
740	Yes	4.934	1.51	4.934	0.46	4.936	0.35	40
760	Yes	5.056	-0.21	5.064	-0.04	5.067	-0.01	39
780	Yes	5.189	-0.28	5.197	-0.08	5.2	-0.06	38
800	Yes	5.322	-0.36	5.33	-0.12	5.333	-0.11	37

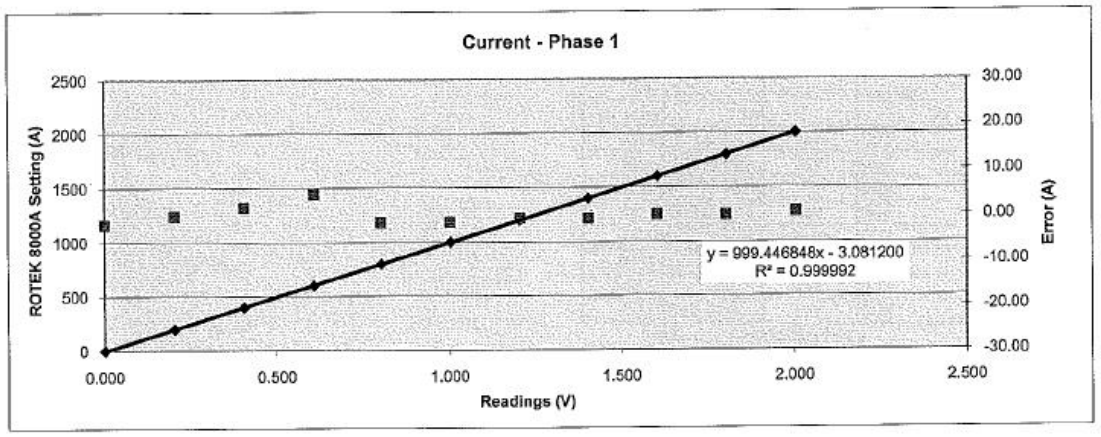
Calculated slope and offset: *TUR is always >4*

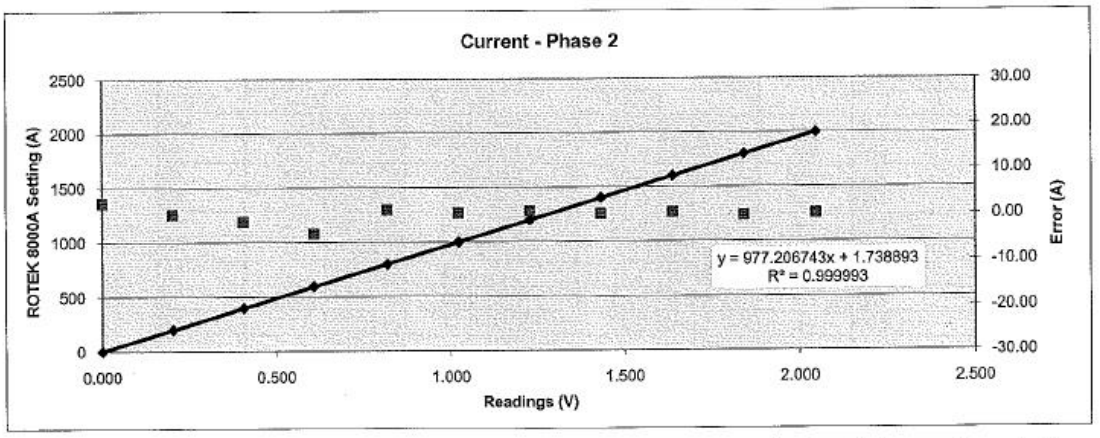
Slope:	149.83	150.05	149.98
Offset:	2.2298598	0.0875835	0.044482

8/17/2010 PQ Sampling System Cal Report (sn PQ05) 100413 20100812 (version 1).xlsx Page 3 of 6

Figure A-3. Calibration sheet for the power transducer (page 3)

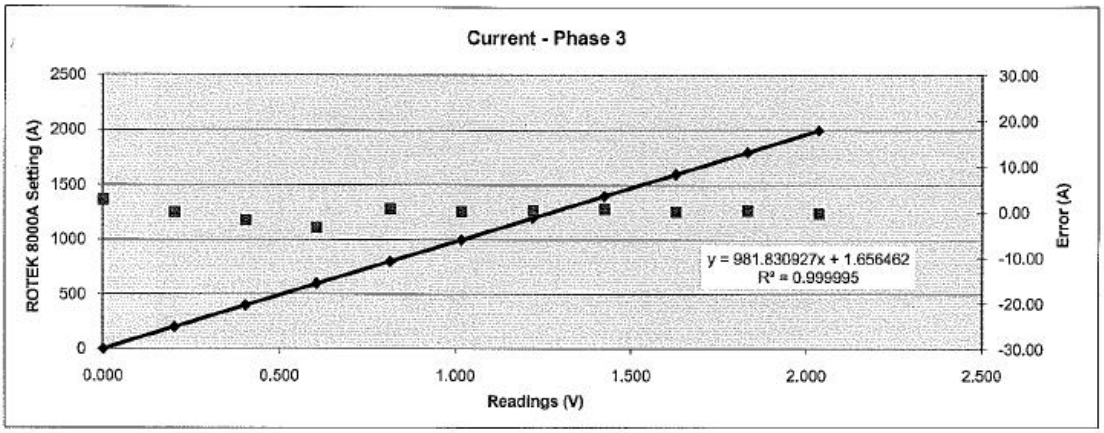


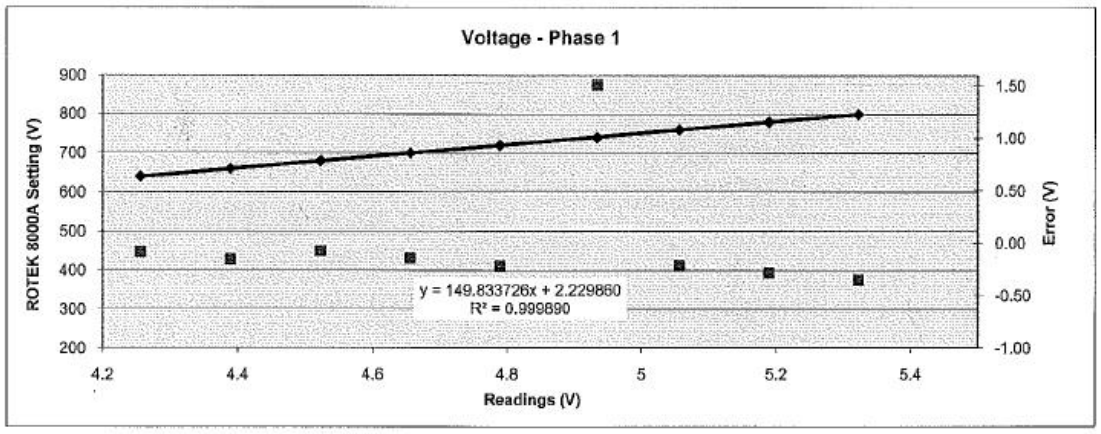




8/17/2010 PQ Sampling System Cal Report (sn PQ05) 100413 20100812 (version 1).xlsx Page 4 of 6

Figure A-4. Calibration sheet for the power transducer (page 4)





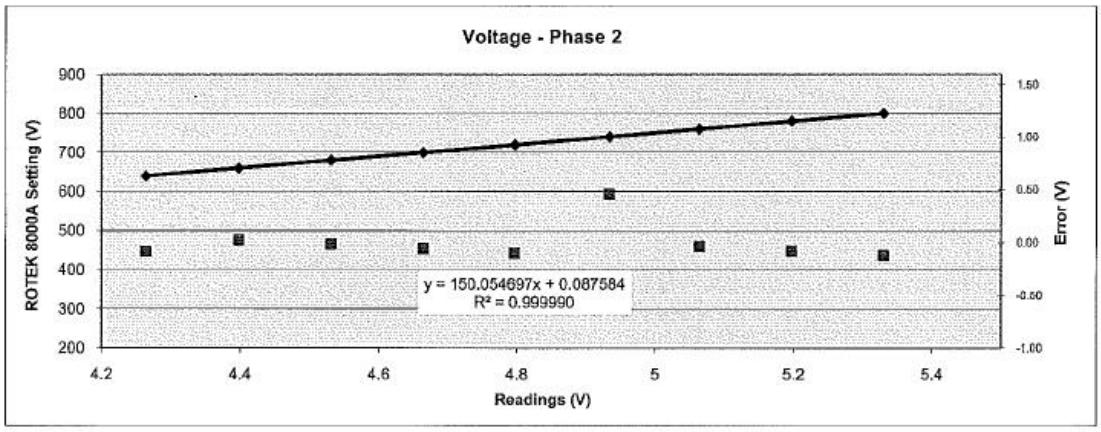


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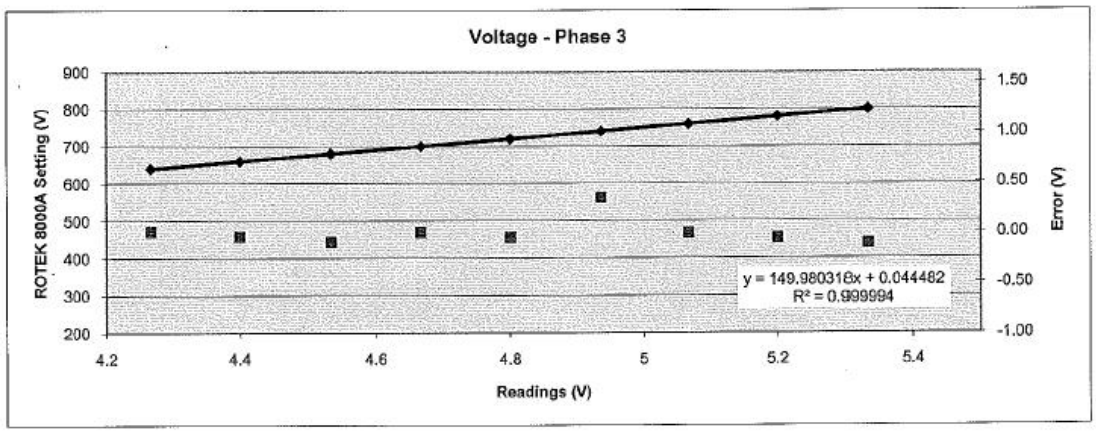
Figure A-5. Calibration sheet for the power transducer (page 5)



8/17/2010 PQ Sampling System Cal Report (sn PQ05) 100413 20100812 (version 1).xlsx Page 6 of 6

Figure A-6. Calibration sheet for the power transducer (page 6)

Wind Speed

DEUTSCHER KALIBRIERDIENST **DKD**

Kalibrierlaboratorium / Calibration laboratory
Akkreditiert durch die / *accredited by the*
Akkreditierungsstelle des Deutschen Kalibrierdienstes

Deutsche WindGuard
Wind Tunnel Services GmbH
Varel

Deutscher Akkreditierungs Rat
DKD-K- 36801

Kalibrierzeichen *Calibration label*	09/5843
	DKD-K-36801
	09/2009

Kalibrierschein
Calibration Certificate

Gegenstand *Object*	Cup Anemometer
Hersteller *Manufacturer*	Thies Clima D-37083 Göttingen
Typ *Type*	4.3351.10.000
Fabrikat/Serien-Nr. *Serial number*	Body: 0909219 Cup: 0909219
Auftraggeber *Customer*	Sky Power International LLC USA - Liberty, SC 29657
Auftragsnummer *Order No.*	VT09556
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	3
Datum der Kalibrierung *Date of calibration*	26.09.2009

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Der DKD ist Unterzeichner der multi- lateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.
This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DKD is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.

Dieser Kalibrierschein darf nur vollständig und unverändert weiterverbreitet werden. Auszüge oder Änderungen bedürfen der Genehmigung sowohl der Akkreditierungsstelle des DKD als auch des ausstellenden Kalibrierlaboratoriums. Kalibrierscheine ohne Unterschrift und Stempel haben keine Gültigkeit.
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Stempel *Seal*	Datum *Date*	Leiter des Kalibrierlaboratoriums *Head of the calibration laboratory*	Bearbeiter *Person in charge*
Deutscher Kalibrierdienst DKD-K- 36801	26.09.2009	Dipl. Phys. D. Westermann	Dipl.-Ing. (FH) M. Meyer zu Himmern

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Figure A-7. Calibration sheet for the primary anemometer (page 1)

Seite 2
Page

09/5843
DKD-K-36801
09/2009

Kalibriergegenstand *Object*	Anemometer		
Kalibrierverfahren *Calibration procedure*	IEC 61400 12 1 - Wind Turbine Power Performance Testing 12 2005 MEASNET - Cup Anemometer Calibration Procedure – 09 1997 ISO 3966 – Measurement of fluid in closed conduits - 1977		
Ort der Kalibrierung *Place of calibration*	Windtunnel of Deutsche WindGuard, Varel		
Messbedingungen *Test Conditions*	wind tunnel area [1]	10000 cm²	
	anemometer frontal area [2]	230 cm²	
	diameter of mounting pipe [3]	34 mm	
	blockage ratio [4]	0.023 [-]	
	blockage correction [5]	1.000 [-]	
	average WindGuard reference [6]	203.8 1/s (Thies First Class)	
	present WindGuard reference [7]	203.7 1/s	
Umgebungsbedingungen *Test conditions*	air temperature	23.3 °C	± 1.0 K
	air pressure	1027.0 hPa	± 1.0 hPa
	relative air humidity	47.6 %	± 2.5 %
Dateiinformation *File info*			
Anmerkungen *Remarks*		-	
Auswertesoftware *Software version*		4.0	

[1] Querschnittsfläche der Auslassdüse des Windkanals
[2] Vereinfachte Querschnittsfläche (Schattenwurf) des Prüflings inkl. Montagerohr
[3] Durchmesser des Montagerohrs
[4] Verhältnis von 2) zu 1)
[5] Korrekturfaktor durch die Verdrängung der Strömung durch den Prüfling
[6] Referenzwert des Referenzanemometers bei 10 m/s (Mittelwert)
[7] Aktueller Wert des Referenzanemometers

Dieser Kalibrierschein wurde elektronisch erzeugt
This calibration certificate has been generated electronically

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Figure A-8. Calibration sheet for the primary anemometer (page 2)

09/5843
DKD-K-36801
09/2009

Kalibrierergebnis:
Result:

Test Item (1/s)	Tunnel Speed (m/s)	Uncertainty (k=2) (m/s)
86.363	4.193	0.10
129.019	6.143	0.10
170.212	8.052	0.10
210.679	9.898	0.10
253.862	11.878	0.10
297.703	13.858	0.10
339.982	15.828	0.11
317.337	14.775	0.10
276.809	12.867	0.10
232.163	10.870	0.10
190.126	8.932	0.10
148.153	7.021	0.10
108.825	5.222	0.10

Angegeben ist die erweiterte Messunsicherheit, die sich aus der Standardmessunsicherheit durch Multiplikation mit dem Erweiterungsfaktor k=2 ergibt. Sie wurde gemäß DKD-3 ermittelt. Der Wert der Messgröße liegt mit einer Wahrscheinlichkeit von 95 % im zugeordneten Wertintervall.

Der Deutsche Kalibrierdienst ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine. Die weiteren Unterzeichner innerhalb und außerhalb Europas sind den Internetseiten von EA (www.european-accreditation.org) und ILAC (www.ilac.org) zu entnehmen.

The expanded uncertainty assigned to the mea-surement results is obtained by multiplying the standard uncertainty by the coverage factor k = 2. It has been determined in accordance with DKD-3. The value of the measurand lies within the assigned range of values with a probability of 95%.

The DKD is signatory to the multilateral agree-ments of the European co-operation for Accredita-tion (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.

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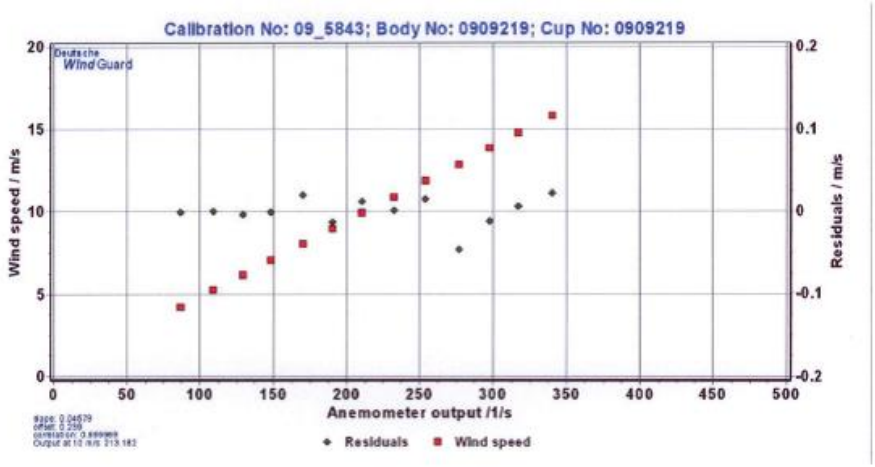
Figure A-9. Calibration sheet for the primary anemometer (page 3)

1 Detailed MEASNET[1] Calibration Results

DKD calibration no.	09/5843
Body no.	0909219
Cup no.	0909219
Date	26.09.2009
Air temperature	23.3 °C
Air pressure	1027.0 hPa
Humidity	47.6 %

Linear regression analysis

Slope	0.04579 (m/s)/(1/s) ±0.00006 (m/s)/(1/s)
Offset	0.239 m/s ±0.015 m/s
St.err(Y)	0.017 m/s
Correlation coefficient	0.999989
Remarks	no



[1]) According to MEASNET Cup Anemometer Calibration Procedure 09/1997.
Deutsche WindGuard Wind Tunnel Services is accredited by MEASNET and by the Deutscher Kalibrierdienst – DKD (German Calibration Service). Registration: DKD – K – 36801

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Figure A-10. Calibration sheet for the primary anemometer (page 4)

2 Instrumentation

Pos.	Sensor	Manufa.	Identification	Year	Calibration
1	Pitot static tube	Airflow	483/8 Nr. 000142	02	06/02
2	Pitot static tube	Airflow	483/8 Nr. 000143	02	06/02
3	Pitot static tube	Airflow	483/8 Nr. 000144	02	06/02
4	Pitot static tube	Airflow	483/8 Nr. 000145	02	06/02
5	Pressure transducer	Setra	C 239 Nr. 1688081	02	DWG12/07
6	Pressure transducer	Setra	C 239 Nr. 1688082	02	DWG12/07
7	Pressure transducer	Setra	C 239 Nr. 1688083	02	03/07
8	Pressure transducer	Setra	C 239 Nr. 1688084	02	03/05
9	El. Barometer	Vaisala	100 A Nr. X2010004	02	DWG12/07
10	El. Thermometer	Galltec	KPK 1/6-ME	02	DWG12/07
11	El. Humidity sensor	Galltec	KPK 1/6-ME	02	DWG12/07
12	Wind tunnel control	-	-	-	-
13	CAN-BUS / PC	esd	-	04	05/04
14	Anemometer		-		
15	Universal Isolator	Knick	P2700 - 58285/8198430	05	01/06

Table 1 Description of the data acquisition system

3 Photo of the calibration set-up

Calibration set-up of the anemometer calibration in the wind tunnel of Deutsche WindGuard, Varel.
The anemometer shown is of the same type as the calibrated one.
Remark: The proportion of the set-up are not true to scale due to imaging geometry.

4 Deviation to MEASNET procedure

The calibration procedure is in all aspects in accordance with the IEC 61400-12-1 Procedure

5 References

[1] J. Mander, D. Westermann, 12/2007 - Verfahrensanweisung DKD-Kalibrierung von Windgeschwindigkeitssensoren
[2] IEC 61400-12-1 12/2005 - Wind Turbine Power Performance Testing
[3] ISO 3966 1977 - Measurement of fluid flow in closed conduits
[4] MEASNET 09 1997 - Cup Anemometer Calibration Procedure

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Figure A-11. Calibration sheet for the primary anemometer (page 5)