Wind Turbine Generator System Power Quality Test Report for the Gaia Wind 11-kW Wind Turbine

Amy Curtis and Vahan Gevorgian

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Wind Turbine Generator System

Power Quality Test Report

for the

Gaia Wind 11-kW Wind Turbine

in

Boulder, CO

Conducted for

National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401

Conducted by

Wind Energy Program
DOE / NREL

Amy Curtis, Vahan Gevorgian

October 12, 2010

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1.0 Background

This test is being conducted as part of the U.S. Department of Energy's (DOE) Independent Testing project. This project was established to help reduce the barriers of wind energy expansion by providing independent testing results for small turbines. In total, five turbines are being tested at the NWTC as a part of this project. Power quality testing is one of up to five tests that may be performed on the turbines, including power performance, safety and function, noise, and duration tests. The results of the testing will provide the manufacturers with reports that may be used for small wind turbine certification.

2.0 Test Summary

This test was conducted in accordance with the International Electrotechnical Commission's (IEC) standard, Measurement and Assessment of Power Quality Characteristics of Grid Connected Wind Turbines, IEC61400-21, First Edition, 2001-12.

The power quality test for the Gaia Wind 11-kW wind turbine began on July 23, 2009 and ended on January 15, 2010. About 9,995 10-min intervals of data were collected while the turbine was available. The IEC 61400-21 Power Quality Standard requires at least five 10-min average data points for each 1 m/s wind speed bin for the wind turbulence intensity between 8 and 16%. This condition reduced the valid data to 1,021 10-min intervals. The highest bin filled (with no wind speed normalization) was the 14 m/s bin. When the data is binned by percent of rated power, more than five data points were recorded for each bin. According to the IEC 61400-21, not enough data was collected to fill the 15 m/s bin due to high turbulence intensity for the data points collected in the 15 m/s bin. The test matrix is given in Appendix A.

The test was conducted in accordance IEC 61400-21 Power Quality Standard and MEASNET procedures, and the following are the test results required by the standard and are included in this report:

- Maximum measured power (60-sec and 0.2-sec), reactive power demand
- Voltage fluctuations (flicker)
- Voltage harmonics, current harmonics, interharmonics and distortions
- Turbine start and stop tests

3.0 Continuous Operation Test Results

3.1 Wind Turbine Data

Table 1: Gaia Wind 11-kW wind turbine general data

Turbine make, model, serial number, production year	Gaia-Wind 11-kW, 10711114, 2007
Wind turbine type	Horizontal axis
Number of blades	2
Hub height (m)	18.2
Blade control	None
Rotor diameter (m)	13
Speed control	Constant speed
Generator type and rating	Induction, 11 kW
Converter type	n/a

Table 2: Wind turbine rated data

Rated power, P_n (kW)	11
Rated wind speed, V_n (m/s)	9.5
Rated apparent power, S_n (kVA)	13
Rated reactive power, Q_n (kvar)	9.6
Rated current, I_n (A)	16
Rated voltage, V_n (V)	480

Table 3: Maximum permitted power

Peak continuous power, P_{mc} (kW)	20
Normalized value, $p_{mc}=P_{mc}/P_n$	1.2

3.2 Active Power, Reactive Power and Power Factor

The relationship between active and reactive power was measured at the wind turbine low voltage (480 VAC) terminals. Only 10-min data points, with turbulence intensity within 8-16% range, were used for this analysis (Figure 1). Power measurements were sampled during continuous operation only, and taken so that at least five 10-min time series of power were collected for each 1 m/s wind speed (according to IEC 61400-21). The sampled data was transferred to 10-minute average data by applying block averaging for each 10-min period (Table 4 and Figure 2). The power factor (Figure 3) was calculated using active and reactive power values. The reactive power demand is shown in Figure 4.

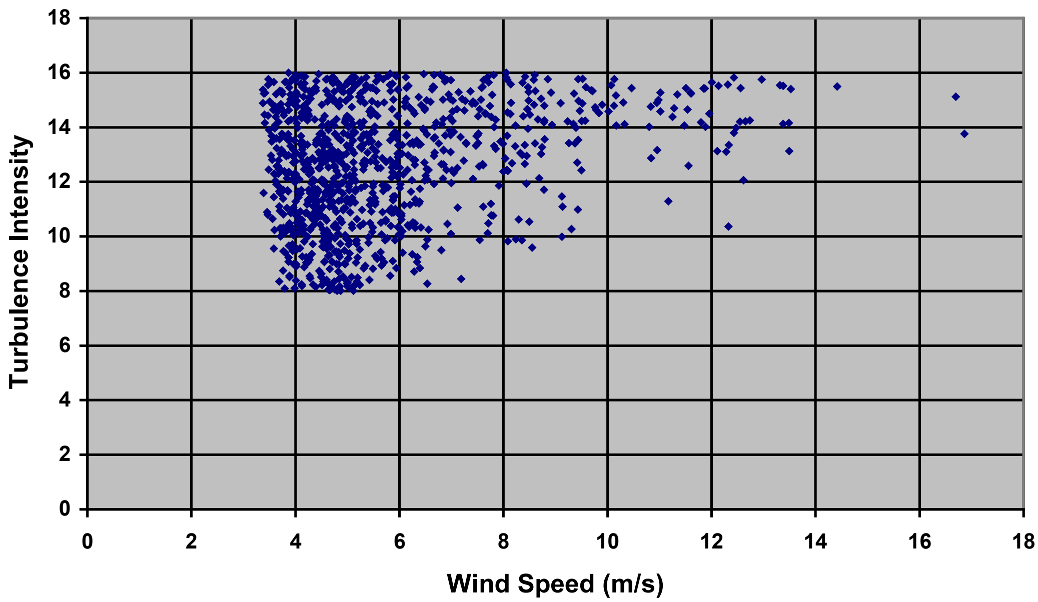


Figure 1: Turbulence intensity vs. wind speed

Table 4: 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	0
3 to 4	142
4 to 5	346
5 to 6	220
6 to 7	112

7 to 8	61
8 to 9	54
9 to 10	29
10 to 11	15
11 to 12	17
12 to 13	16
13 to 14	6
14 to 15	1

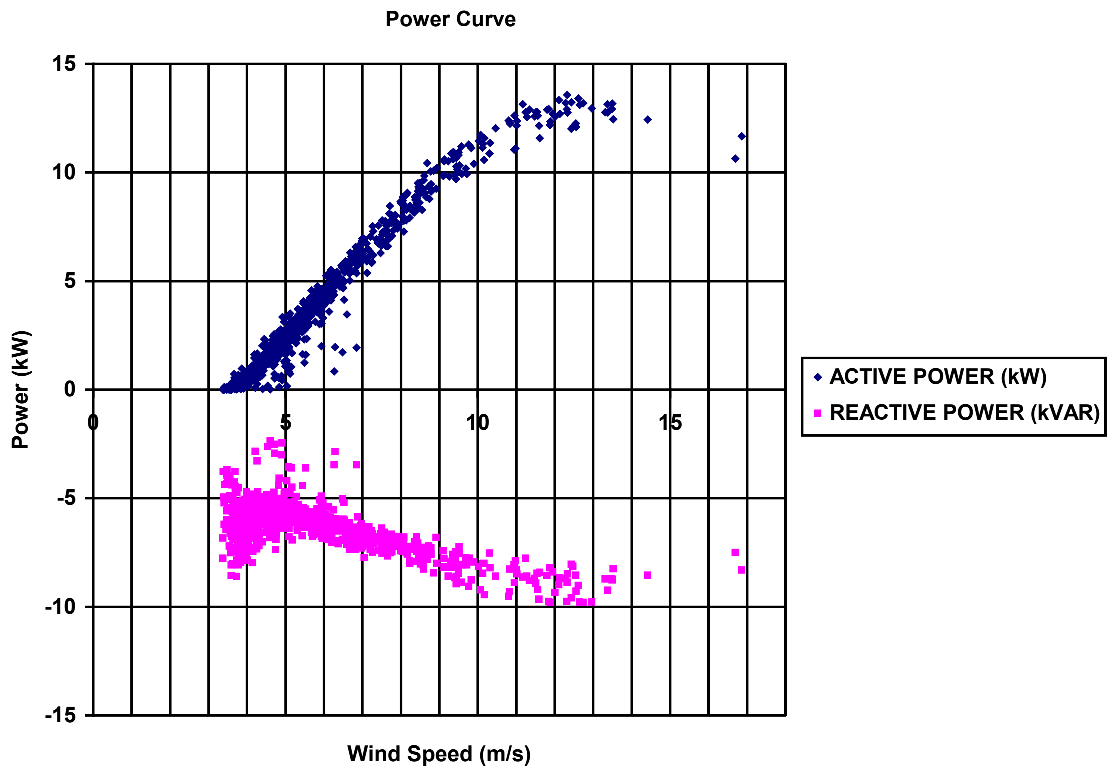


Figure 2: Active and reactive power vs. wind speed

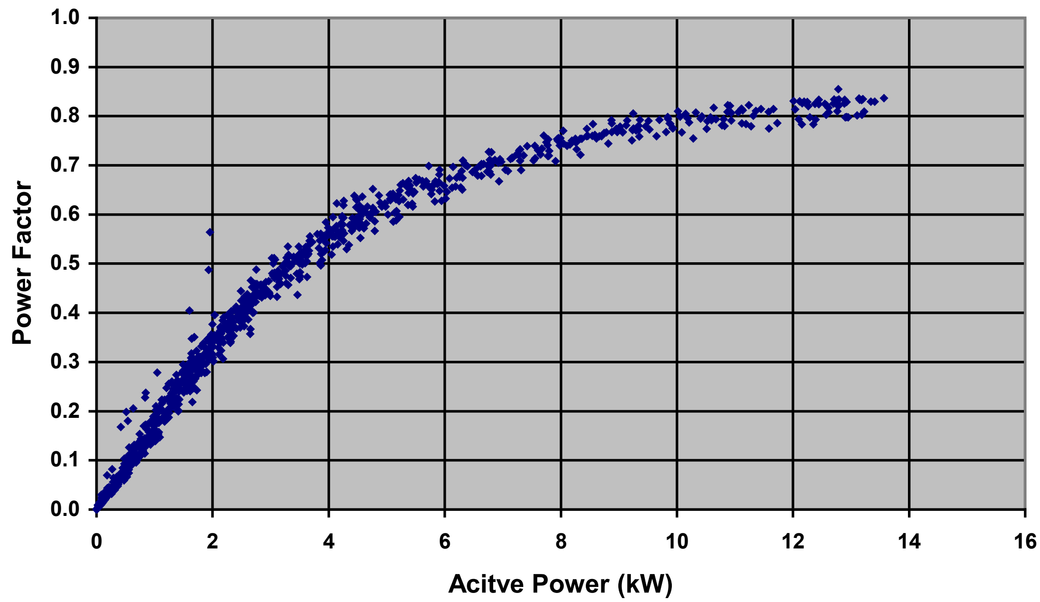


Figure 3: Power factor vs. active power

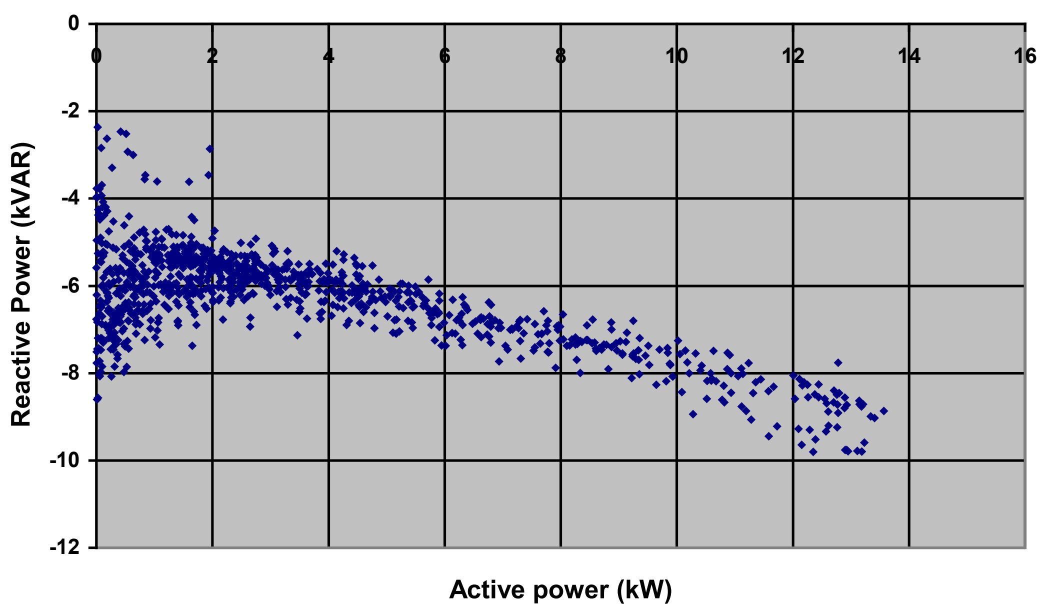


Figure 4: Reactive Vs. Active Power

The 10-min average data was sorted according to the method of bins so that the reactive power could be specified for 0, 10, …., 90, 100% of rated power (Table 5). The maximum active power was measured both as 60-sec (P60) and 0.2-sec average (P0.2) values. The reactive power at P_{mc} , P_{60}, and $P_{0.2}$ was determined by extrapolation of the measured relation between the active and reactive power (Table 6).

Table 5: Data binned by real power

Power Bin (% of rated power)	Number of 10-min data points per bin	Output power, bin-mean-value (kW)	Reactive power, bin-mean-value (kVAR)
-5 to 5	161	0.238	-6.118
5 to 15	223	1.111	-5.695
15 to 25	182	2.180	-5.682
25 to 35	97	3.266	-5.844
35 to 45	86	4.325	-6.088
45 to 55	59	5.473	-6.493
55 to 65	43	6.594	-6.870
65 to 75	35	7.677	-7.116
75 to 85	38	8.795	-7.383
85 to 95	24	9.909	-7.807
95 to 105	25	10.932	-8.202
105 to 115	24	12.210	-8.792

Table 6: Maximum instantaneous real and reactive power

Max. permitted power, P_{mc}:		**60-sec average:**		**0.2-sec average:**	
P_{mc}, kW **15.00**	$p_{mc}=P_{mc}/P_n$ **1.36**	P_{60}, kW **13.94**	$p_{60}=P_{60}/P_n$ **1.27**	$P_{0.2}$, kW **19.62**	$p_{0.2}=P_{0.2}/P_n$ **1.78**
Q_{mc} at P_{mc}, kVAR **-10.51**	$q_{mc}=Q_{mc}/P_n$ **-0.96**	Q_{60} at P_{60}, kVAR **-9.78**	$q_{60}=Q_{60}/P_n$ **-0.89**	$Q_{0.2}$ at $P_{0.2}$, kVAR **-15.77**	$q_{0.2}=Q_{0.2}/P_n$ **-1.43**

Note 1: Data were not normalized to sea-level density.

Note 2: The active power curve shown in Figure 2 may not be used for the Gaia Wind 11-kW wind turbine power performance evaluation. The official power curve will be published in the Gaia Wind 11-kW Power Performance Test Report.

3.3 Line Voltage Distortions

The average voltage Total Harmonic Distortions (THD) measured during the test are shown below for each phase:

Phase A – **2.028** %

Phase B – **1.798** %

Phase C – **1.734** %

The maximum voltage THDs measured during the test are shown below for each phase:

Phase A – **4.163** %

Phase B – **4.028** %

Phase C – **3.595** %

All voltage THDs were calculated from harmonic voltages. The harmonic voltages were subgrouped according to Section 5.6 of IEC 61000-4-7/CDV. The window width used during measurements $T_w=12$.

3.4 Current Harmonics

The individual harmonic currents during continuous operation were measured as 10-min average data for each harmonic order (up to 50th) at the output power giving the maximum individual harmonic current. The harmonic data and the maximum current Total Demand Distortion (TDD) values as a percentage of nominal current I_n are shown in Table 7. Figure 5 shows the plots of 10-min average data for maximum current TDD (% of I_n) as a function of output power.

Table 7: Maximum Current Harmonics (10 min averages)

Order	**Phase A**		**Phase B**		**Phase C**	
	Power (kW)	Harm. current (%)	Power (kW)	Harm. current (%)	Power (kW)	Harm. current (%)
1	11.665	115.845	11.665	115.995	11.665	115.717
2	1.424	1.267	13.228	0.597	1.424	1.507
3	1.424	9.443	1.424	10.264	1.721	4.519
4	1.424	0.702	1.424	0.479	1.424	0.412
5	6.304	5.410	7.088	4.198	2.307	6.006
6	1.424	0.486	1.424	0.273	1.424	0.424
7	7.752	4.204	7.752	4.482	7.552	3.781
8	1.424	0.372	1.424	0.292	4.310	0.217
9	1.721	1.103	1.037	1.312	1.721	0.990
10	11.446	0.257	11.446	0.222	11.446	0.208
11	4.513	6.854	4.513	5.849	4.513	5.838
12	0.956	0.226	1.669	0.213	1.970	0.215
13	4.109	6.692	7.782	4.816	4.109	6.492
14	3.504	0.532	3.504	0.449	3.504	0.512
15	2.256	1.563	1.410	1.533	4.709	0.898
16	4.310	0.681	4.310	0.665	4.310	0.728
17	7.782	2.590	7.782	3.611	6.759	3.639
18	4.310	1.588	4.310	1.624	4.310	1.781
19	4.310	4.030	4.310	3.817	4.310	3.915
20	4.310	3.112	4.310	3.603	4.310	3.475
21	4.310	4.473	4.310	4.992	4.310	4.747
22	4.310	5.335	4.310	5.438	4.310	5.855
23	4.310	7.574	4.310	7.016	4.310	6.085
24	4.310	5.017	4.310	4.138	4.310	4.303
25	4.310	7.064	4.310	4.774	4.310	6.356
26	4.310	3.218	4.310	2.731	4.310	2.568
27	4.310	2.729	4.310	2.323	4.310	2.058
28	4.310	2.334	4.310	1.935	4.310	1.933

29	4.310	2.444	4.310	2.054	4.310	1.937
30	4.310	1.775	4.310	1.494	4.310	1.518
31	4.310	1.634	4.310	1.344	4.310	1.361
32	4.310	1.488	4.310	1.188	4.310	1.239
33	4.310	1.378	4.310	0.998	4.310	1.083
34	4.310	1.255	4.310	0.901	4.310	1.010
35	4.310	1.354	0.189	1.195	4.310	1.023
36	4.310	0.920	4.310	0.674	4.310	0.755
37	4.310	0.758	4.310	0.596	4.310	0.654
38	4.310	0.636	4.310	0.508	4.310	0.531
39	4.310	0.500	4.310	0.441	4.310	0.389
40	4.310	0.441	4.310	0.379	4.310	0.373
41	7.771	0.555	4.447	0.454	4.447	0.536
42	4.310	0.303	4.310	0.273	4.310	0.251
43	12.112	0.288	12.112	0.288	4.310	0.212
44	4.310	0.216	4.310	0.198	4.310	0.179
45	12.112	0.207	12.112	0.201	4.310	0.137
46	4.310	0.157	4.310	0.145	4.310	0.128
47	4.447	0.232	1.627	0.199	0.845	0.252
48	4.310	0.114	4.310	0.109	4.310	0.091
49	11.579	0.126	11.579	0.149	4.622	0.112
50	4.310	0.086	4.310	0.082	6.731	0.079

Max. phase A current TDD (% of I_n):	***16.823***	**Output power at max current THD (kW):**	***12.780***
Max. phase B current TDD (% of I_n):	***15.113***	**Output power at max current THD (kW):**	***12.780***
Max. phase C current TDD (% of I_n):	***15.316***	**Output power at max current THD (kW):**	***12.780***

The harmonic currents were subgrouped according to Section 5.6 of IEC 61000-4-7/CDV. The window width used during measurements was T_w=*12*.

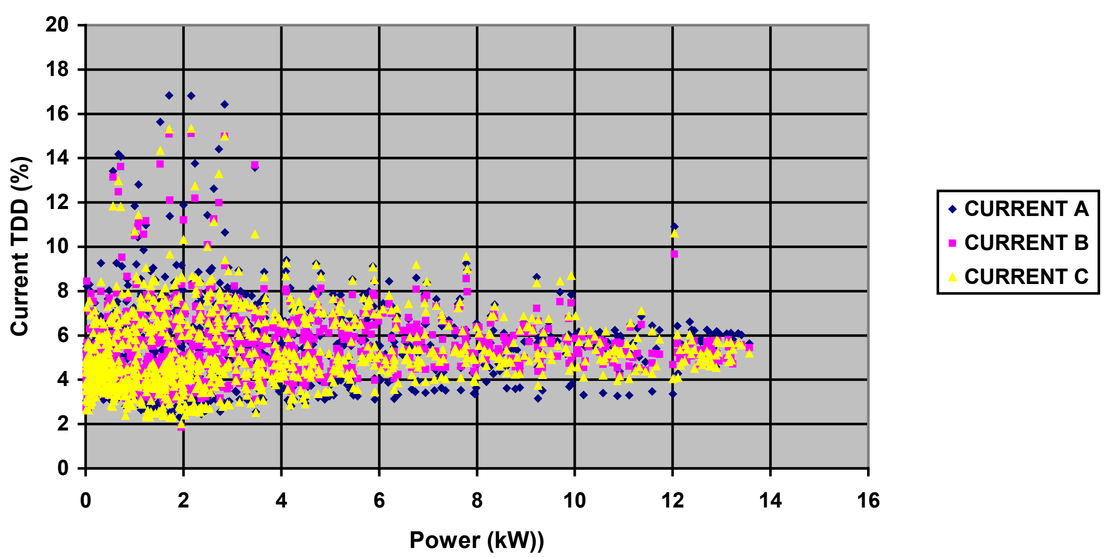


Figure 5: Current TDD Vs. Power

3.5 Current Interharmonics

The individual interharmonic currents below 2 kHz are given in Table 8 as 10-min average values for each frequency at the output power giving the maximum individual interharmonic current.

Table 8: Current Interharmonics

f	Phase A		Phase B		Phase C	
	Power	Interhar. current	Power	Interhar. current	Power	Interhar. current
(Hz)	(kW)	(%)	(kW)	(%)	(kW)	(%)
90	10.868	2.399	10.868	2.428	10.868	2.410
150	0.280	0.728	0.280	0.664	0.280	0.814
210	0.280	0.539	0.280	0.542	0.280	0.457
270	0.280	0.393	0.280	0.332	0.280	0.454
330	0.280	0.328	0.280	0.296	0.280	0.448
390	2.141	0.313	2.141	0.279	0.280	0.290
450	0.736	0.404	0.736	0.380	0.736	0.381
510	0.736	0.271	0.736	0.260	0.736	0.257
570	0.736	0.208	0.736	0.198	0.736	0.201
630	2.735	0.260	2.735	0.241	2.735	0.244
690	2.735	0.321	2.735	0.282	2.735	0.291
750	6.127	0.549	6.127	0.496	6.127	0.499
810	6.127	0.628	6.127	0.559	4.257	0.463
870	0.736	0.442	0.736	0.411	0.736	0.431
930	0.736	0.592	0.736	0.551	0.736	0.605
990	0.736	0.827	0.736	0.787	0.736	0.862
1050	0.736	1.231	0.736	1.199	0.736	1.315
1110	0.736	1.745	0.736	1.832	0.736	1.917
1170	0.736	2.380	0.736	2.733	0.736	2.636
1230	0.736	3.299	0.736	3.855	0.736	3.759
1290	0.736	4.413	0.736	4.923	0.736	5.014
1350	0.736	5.123	0.736	4.980	0.736	5.221
1410	0.736	5.086	0.736	4.348	0.736	4.464
1470	0.736	4.210	0.736	3.548	0.736	3.341
1530	0.736	3.417	0.736	2.884	0.736	2.609
1590	0.736	2.817	0.736	2.402	0.736	2.136
1650	0.736	2.434	0.736	2.065	0.736	1.898
1710	0.736	2.091	0.736	1.768	0.736	1.664
1770	0.736	1.821	0.736	1.552	0.736	1.499
1830	0.736	1.597	0.736	1.343	0.736	1.343
1890	0.736	1.452	0.736	1.189	0.736	1.221
1950	0.736	1.324	0.736	1.054	0.736	1.104
2010	0.736	1.234	0.736	0.927	0.736	1.001
2070	0.736	1.082	0.736	0.798	0.736	0.866
2130	0.736	0.958	0.736	0.696	0.736	0.777
2190	0.736	0.812	0.736	0.606	0.736	0.654
2250	0.736	0.672	0.736	0.528	0.736	0.551
2310	0.736	0.554	0.736	0.460	0.736	0.459
2370	0.736	0.458	0.736	0.397	0.736	0.382
2430	0.736	0.374	0.736	0.341	0.736	0.317
2490	0.736	0.323	0.736	0.297	0.736	0.276
2550	0.736	0.271	0.736	0.252	0.736	0.235
2610	0.736	0.233	0.736	0.216	0.736	0.200
2670	12.778	1.091	12.778	1.049	12.778	1.013
2730	0.736	0.175	0.736	0.164	6.127	0.163
2790	12.778	1.216	12.778	1.302	12.778	1.066

2850	6.127	0.146	6.127	0.135	6.127	0.153
2910	6.127	0.141	6.127	0.131	6.127	0.149
2970	6.127	0.138	6.127	0.128	6.127	0.145
3030	12.778	0.817	12.778	0.734	12.778	0.700

The interharmonic currents were subgrouped according to Annex A of IEC 61000-4-7/CDV. The window width used during measurements $T_w=12$.

3.6 Current Distortions

The individual current distortions in the range 2 kHz up to 9 kHz are given in Table 9 as 10-min average values for each frequency at the output power giving the maximum individual current distortion.

Table 9: Current Distortions (2 - 9 kHz range)

f (kHz)	Phase A		Phase B		Phase C	
	Power (kW)	Interhar. current (%)	Power (kW)	Interhar. current (%)	Power (kW)	Interhar. current (%)
0.1	12.793	117.017	12.793	117.322	12.793	119.634
0.3	4.644	6.863	4.644	5.452	4.644	6.972
0.5	7.752	4.236	7.752	4.502	7.552	3.803
0.7	1.037	8.403	1.037	6.910	4.109	7.523
0.9	2.149	3.642	2.149	3.749	2.149	3.807
1.1	1.231	11.490	1.231	12.014	1.231	11.859
1.3	2.149	47.437	2.149	56.479	2.149	40.754
1.5	2.149	38.814	2.149	29.895	2.149	31.273
1.7	1.231	11.770	1.231	10.320	1.231	8.660
1.9	1.231	6.658	1.231	5.841	1.231	5.816
2.1	2.149	14.726	2.149	13.327	2.149	14.368
2.3	2.149	14.279	2.149	11.802	2.149	11.549
2.5	2.149	2.349	2.149	1.851	2.149	1.890
2.7	1.231	2.275	1.231	2.106	1.231	2.077
2.9	2.149	7.109	2.149	6.443	2.149	6.227
3.1	1.231	1.477	1.231	1.445	1.231	1.358
3.3	2.149	0.463	2.149	0.378	2.149	0.417
3.5	2.149	1.189	2.149	1.062	2.149	1.146
3.7	2.149	0.911	1.231	0.784	2.149	0.792
3.9	2.149	0.265	2.149	0.234	2.149	0.197
4.1	2.149	0.346	2.149	0.256	1.231	0.276
4.3	1.231	1.019	1.231	0.735	1.231	0.862
4.5	2.149	0.307	1.231	0.284	2.149	0.239
4.7	1.231	0.254	1.231	0.267	1.231	0.208
4.9	1.231	0.610	1.231	0.659	1.231	0.656
5.1	1.231	0.621	1.231	0.619	1.231	0.424
5.3	1.231	0.145	1.231	0.162	1.231	0.151
5.5	1.231	0.193	1.231	0.198	1.231	0.169
5.7	1.231	0.322	1.231	0.273	1.231	0.301
5.9	1.231	0.268	1.231	0.289	1.231	0.196
6.1	1.231	0.135	1.231	0.113	1.231	0.111
6.3	1.231	0.090	1.231	0.100	1.231	0.086
6.5	1.231	0.128	1.231	0.136	1.231	0.129
6.7	2.149	0.070	2.149	0.074	1.231	0.060
6.9	2.149	0.065	1.231	0.065	1.231	0.055
7.1	2.149	0.078	2.149	0.079	2.904	0.077
7.3	2.149	0.086	2.149	0.073	2.149	0.069
7.5	2.149	0.060	2.149	0.061	1.231	0.050
7.7	2.149	0.064	2.149	0.063	2.149	0.055
7.9	2.149	0.087	2.149	0.083	2.149	0.076
8.1	2.149	0.062	2.149	0.065	2.149	0.054
8.3	2.149	0.057	1.231	0.059	1.231	0.049
8.5	1.231	0.064	2.149	0.064	2.149	0.063

8.7	2.149	0.064	2.149	0.063	2.149	0.055
8.9	2.149	0.053	2.149	0.054	1.231	0.047

The current distortions were measured and evaluated according to Annex B of IEC 61000-4-7/CDV. The window width used during measurements $T_w=12$.

3.7 Current and Voltage Imbalance

Figure 6 and Figure 7 show the voltage and current imbalance observed during the testing. The current and voltage imbalance was calculated for each 10-min period. The values are plotted against the average power of each 10-min data set.

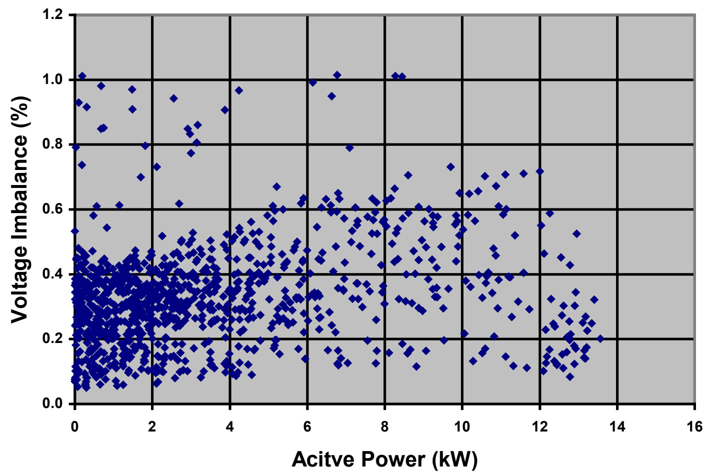


Figure 6: Voltage Imbalance Vs. Power

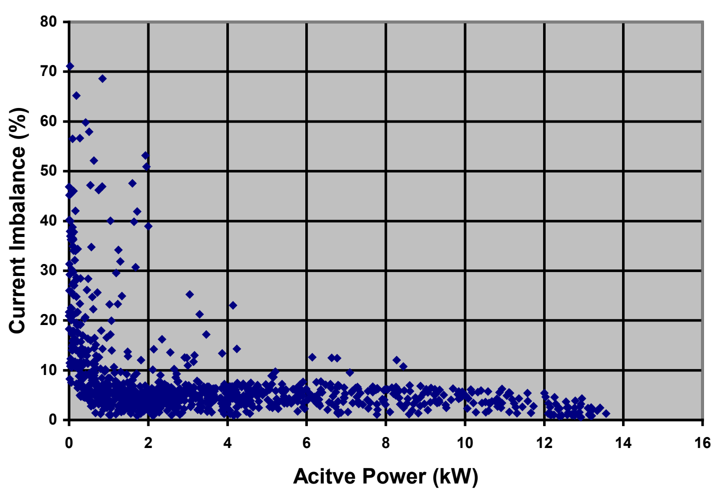


Figure 7: Current imbalance Vs. Power

3.8 Continuous Operation Flicker

The flicker coefficients $C(\Psi_k, V_a)$ were determined according to procedures listed in IEC61400-21. The flicker measuring and analysis methods are described in the standard. Total number of 10-min interval data collected for this test: N_{bin}=1021.

Figure 8, Figure 9, Figure 10, and Figure 11 show the graphs of fictitious grid flicker coefficients as a function of 10-min average active power for four different impedance phase angles (30°, 50°, 70° and 85°). The resulting flicker coefficients for continuous operation are shown in Table 10. 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 is 50. During the power quality test there was a nearby dynamometer test and a neighboring turbine test that were both known to affect the power quality on the grid. These tests may have contributed to the variations in P_{st}.

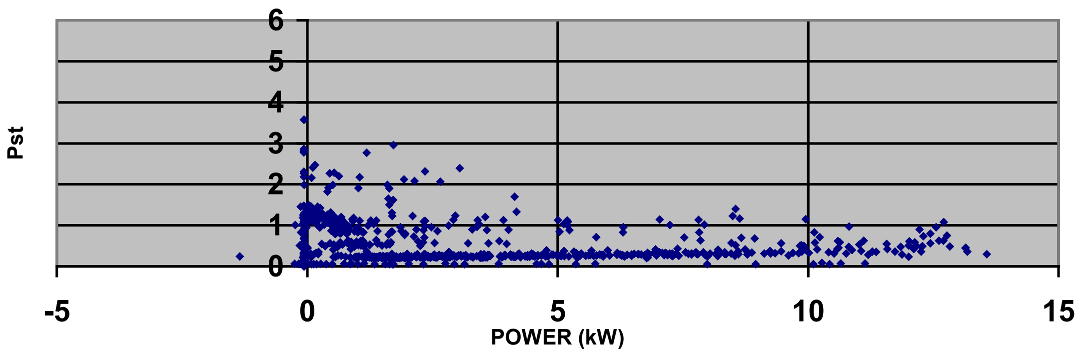


Figure 8: P_{st} vs. power for 30° network impedance angle

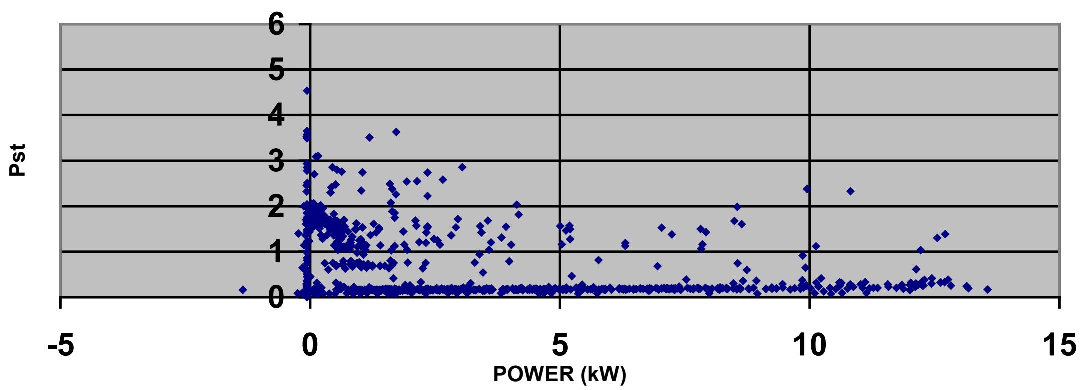


Figure 9: P_{st} vs. power for 50° network impedance angle

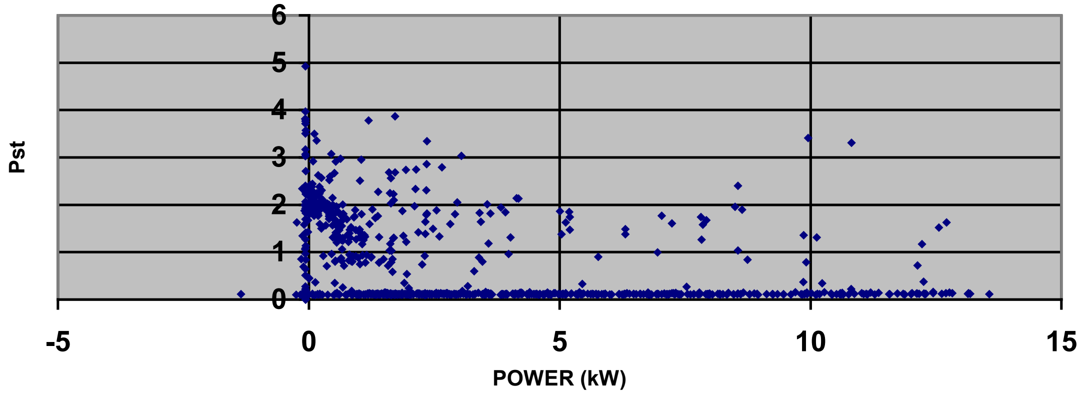


Figure 10: P_{st} vs. power for 70° network impedance angle

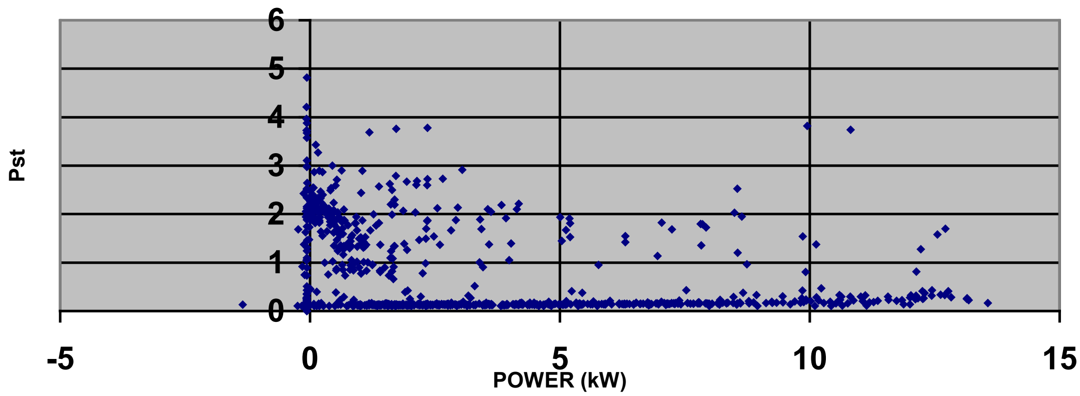


Figure 11: P_{st} vs. power for 85° network impedance angle

The simulated flicker values P_{st} depend on $S_{k.fic}$ and the grid impedance angle. To reduce this dependence, IEC 61400-21 defines flicker coefficients $C(\Psi_k, V_a)$ which are calculated as a normalized quantity according to Equation 6 of the standard (Ψ_k - network impedance phase angle, V_a – annual average wind speed). The flicker coefficient of the wind turbine for the actual Ψ_k and V_a at the site, may be found from the Table 10 by applying linear interpolation.

Table 10: Resulting flicker coefficients in continuous operation

Network impedance phase angle, Ψ_k (deg)	30°	50°	70°	85°
Annual average wind speed, V_a (m/s)	Flicker coefficients, $C(\Psi_k, V_a)$			
6.0	98.42	116.35	125.85	122.40
7.5	97.77	116.35	122.18	119.08
8.5	97.18	116.35	121.93	118.65
10.0	96.37	116.35	120.92	117.95

4.0 Switching Operation Tests Results

4.1 Turbine starts and stops

Normal start tests were conducted at cut-in, moderate, and rated wind speeds. The wind speed was recorded during the tests along with voltage and current waveforms, and 10-min average wind speed during the switching operation was within ± 2 m/s of the required wind speed. The measurements were taken for a period long enough to ensure that the transient of the switching operation was abated, though limited to exclude possible power fluctuations due to turbulence. Table 11 lists the figure numbers for the current waveforms for all starting and stopping cases.

Table 11: Table of Figures for transient waveforms

Wind Regime	Starts	Stops
Cut-in	Figure 12, Figure 13	Figure 16, Figure 17
Rated	Figure 14, Figure 15	Figure 18, Figure 19

The active and reactive powers were calculated for each start and stop case. The time series RMS voltage for Phase A also are shown for each case to illustrate voltage fluctuations during switching operations.

The voltage and current time series were combined in Equation 1 of the standard to simulate 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 12-15).

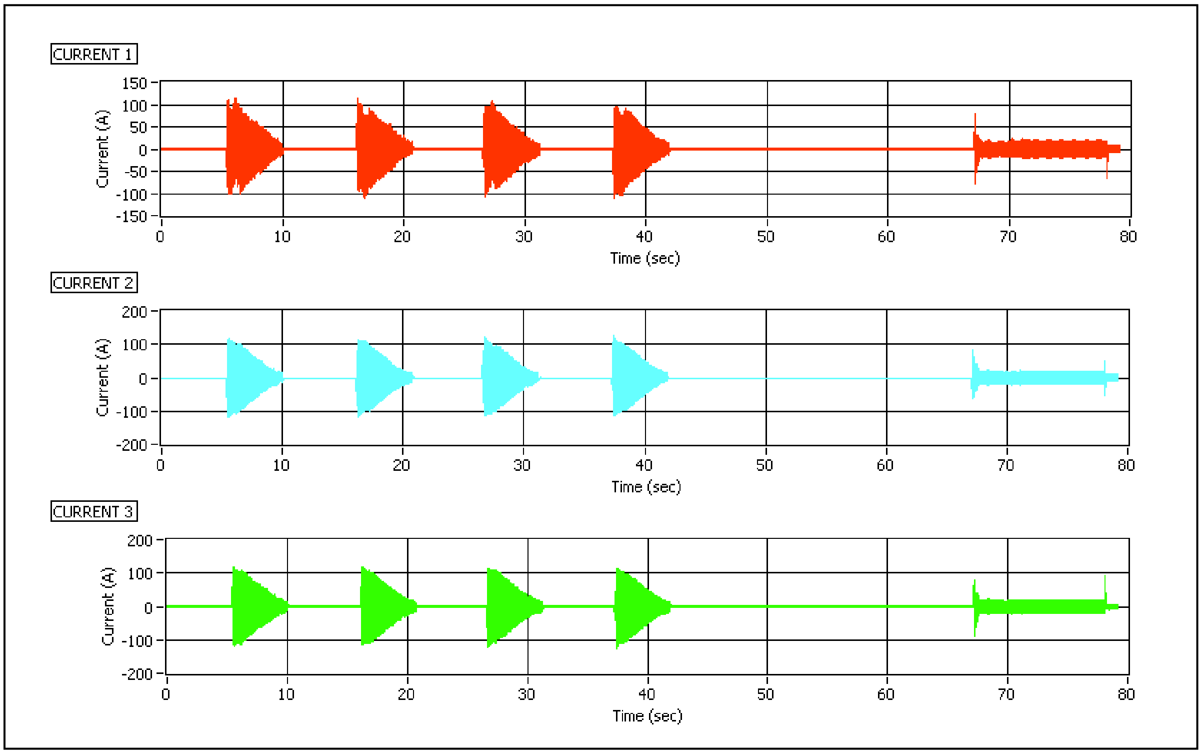


Figure 12: Cut-in wind (4.8 m/s) start: current waveforms (August 19, 2009)

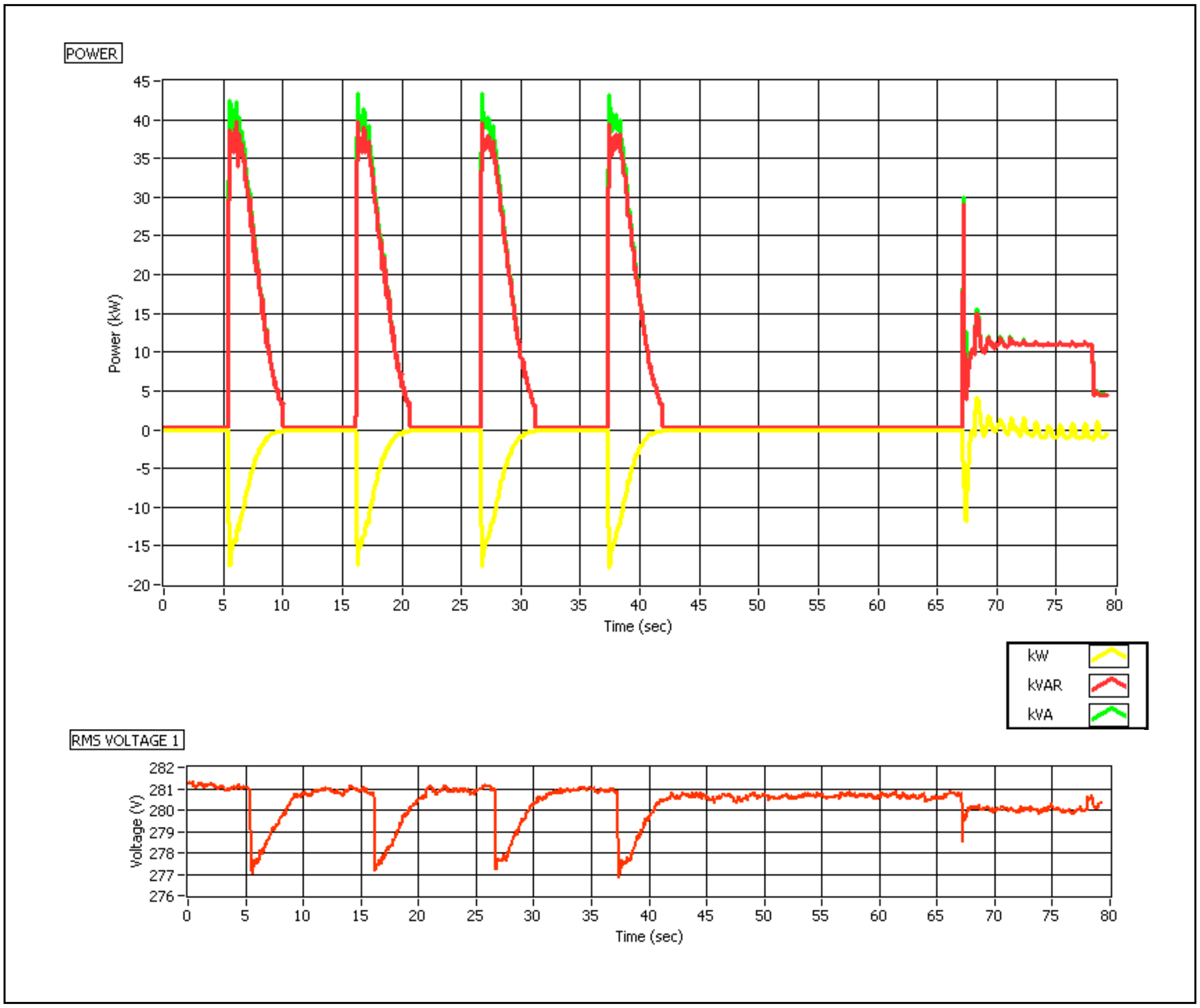


Figure 13: Cut-in wind (4.8 m/s) start: power and RMS voltage (August 19, 2009)

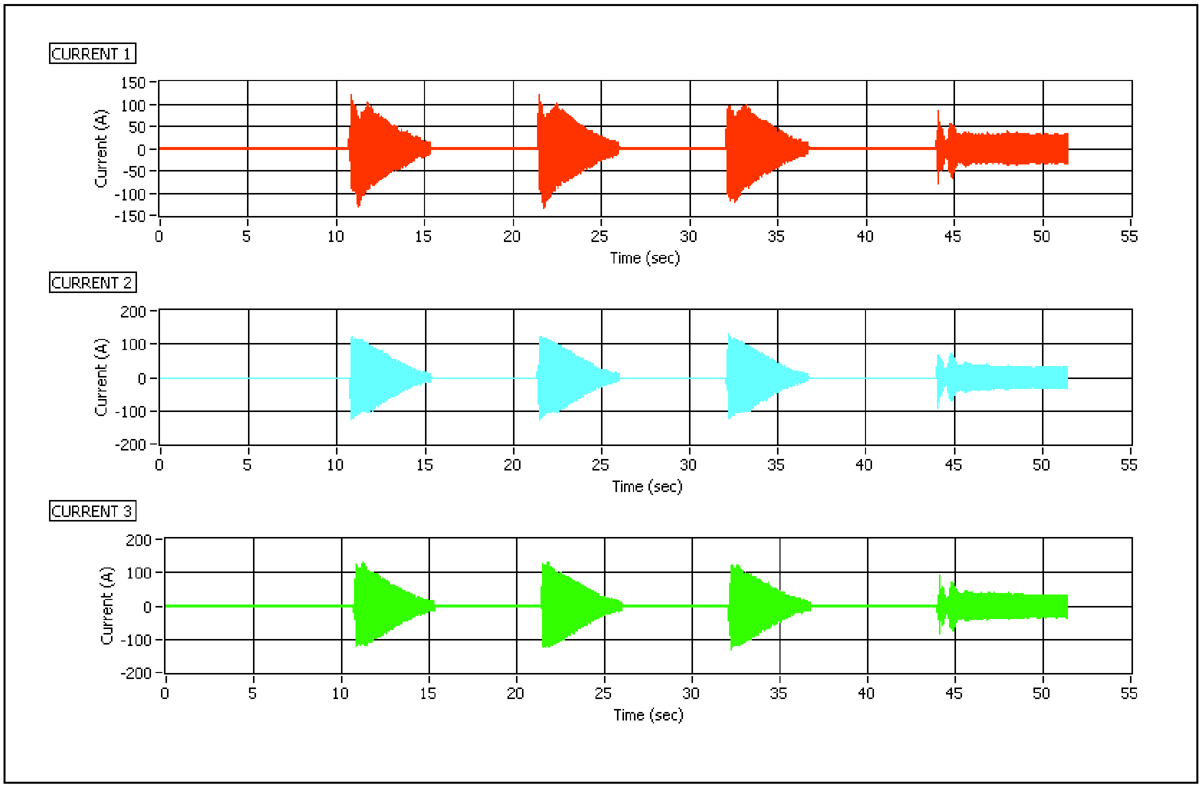


Figure 14: Rated wind (10.5 m/s) start, current waveforms (December 31, 2009)

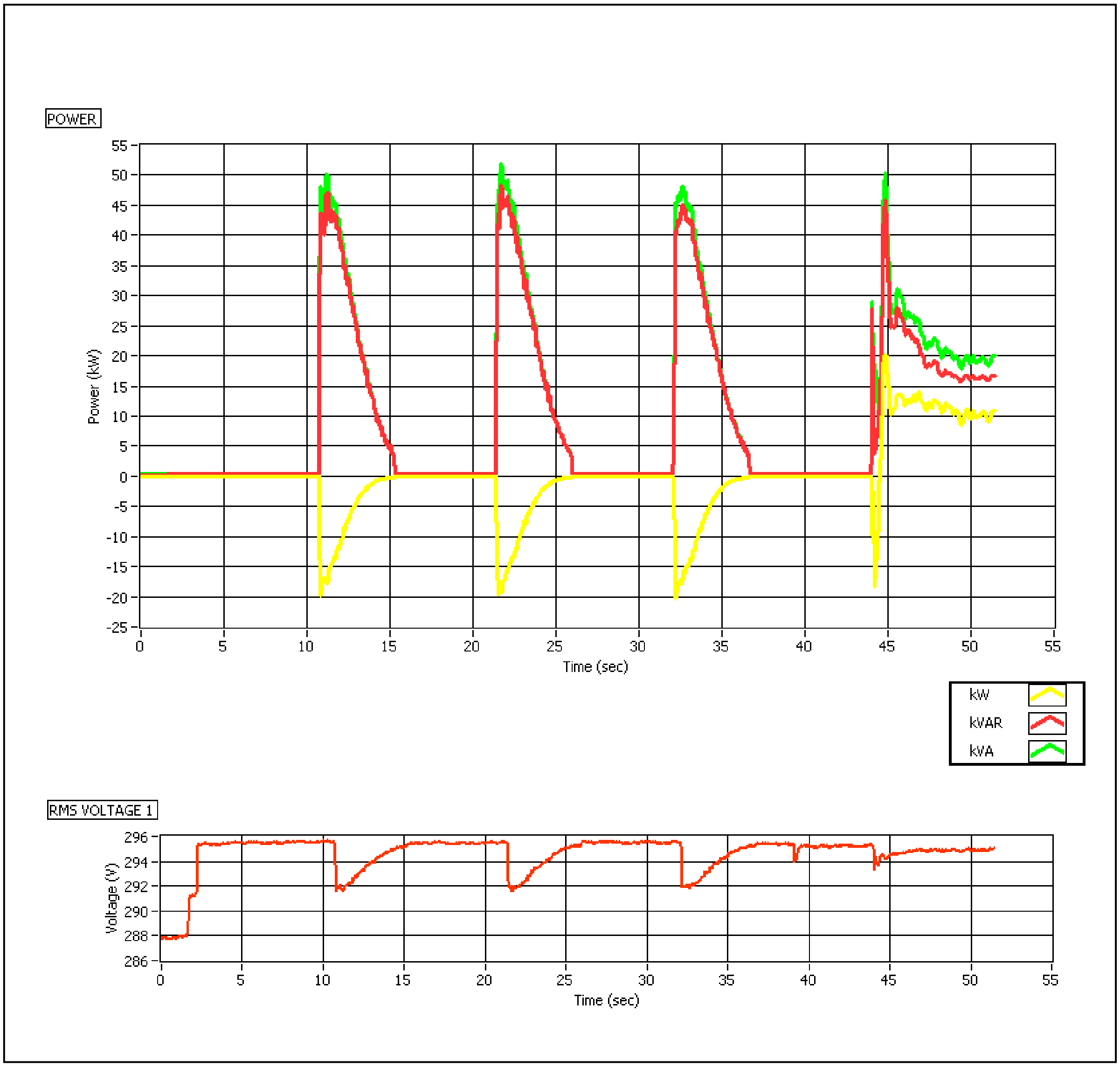


Figure 15: Rated wind (10.5 m/s) start, power, and RMS voltage (December 31, 2009)

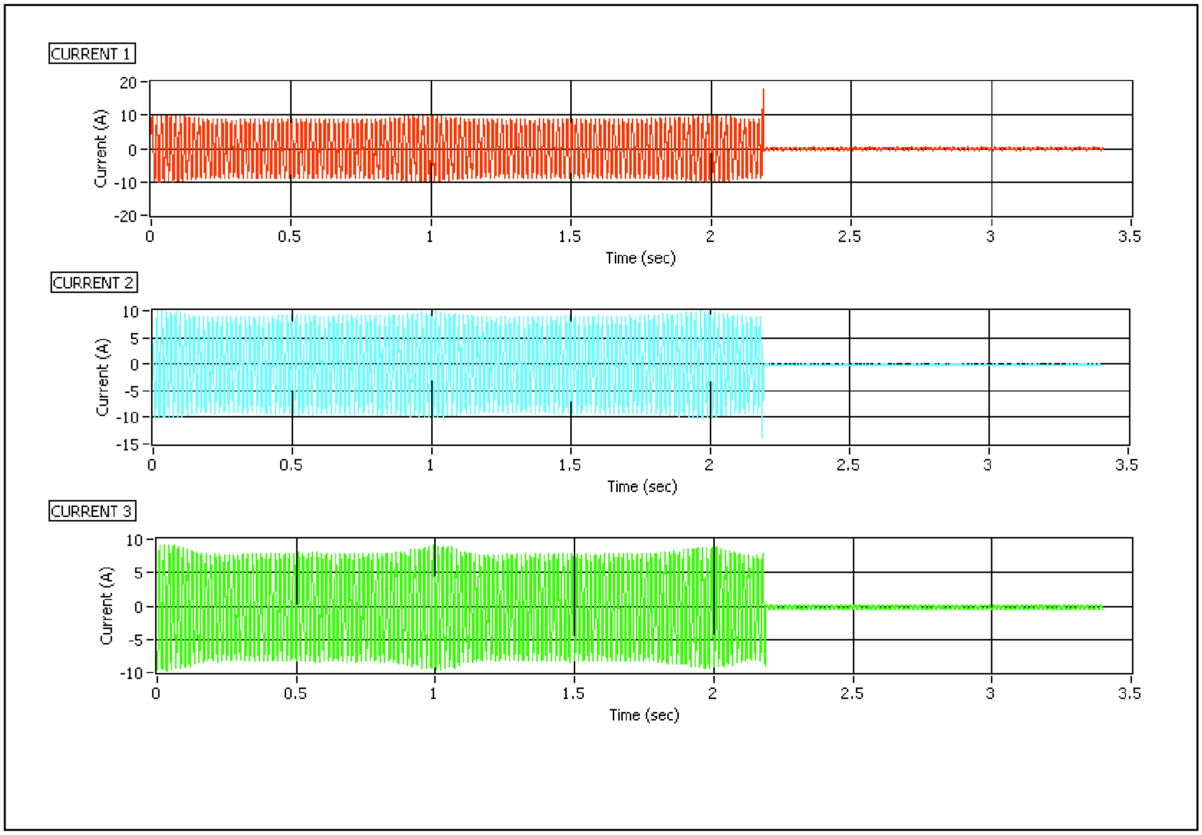


Figure 16: Cut-in wind (3.4 m/s) stop, current waveforms (August 19, 2009)

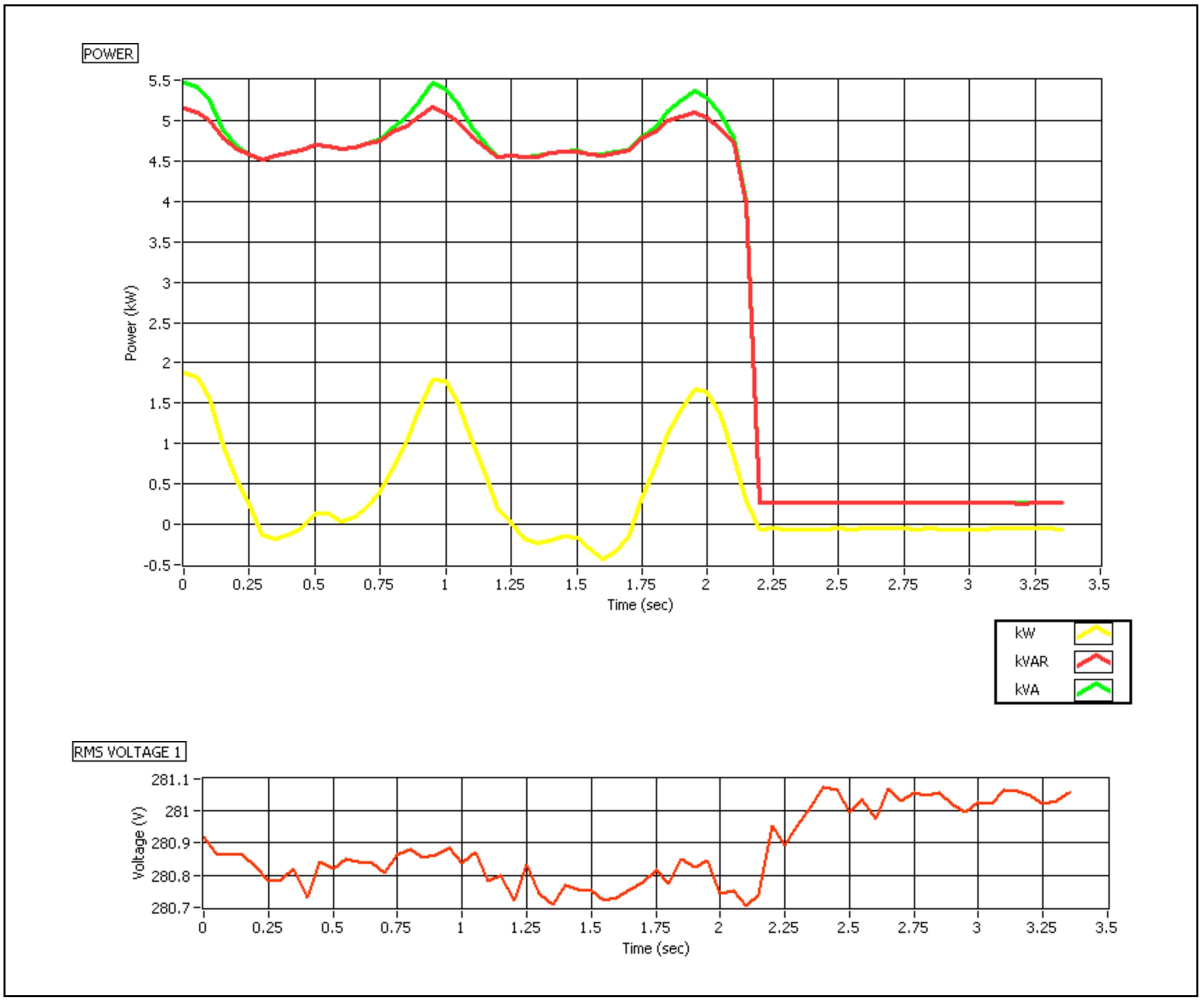


Figure 17: Cut-in wind (3.4 m/s) stop, power, and RMS voltage (August 19, 2009)

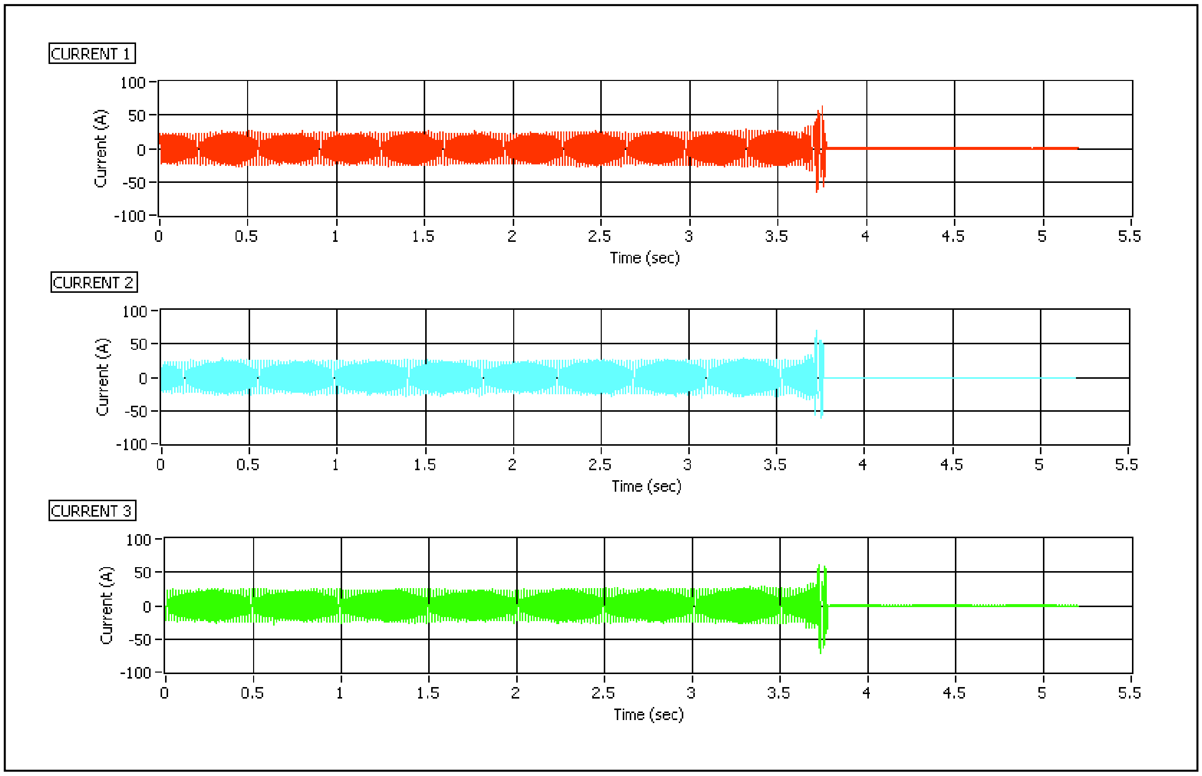


Figure 18: Rated wind (10.0 m/s) stop: current waveforms (December 31, 2009)

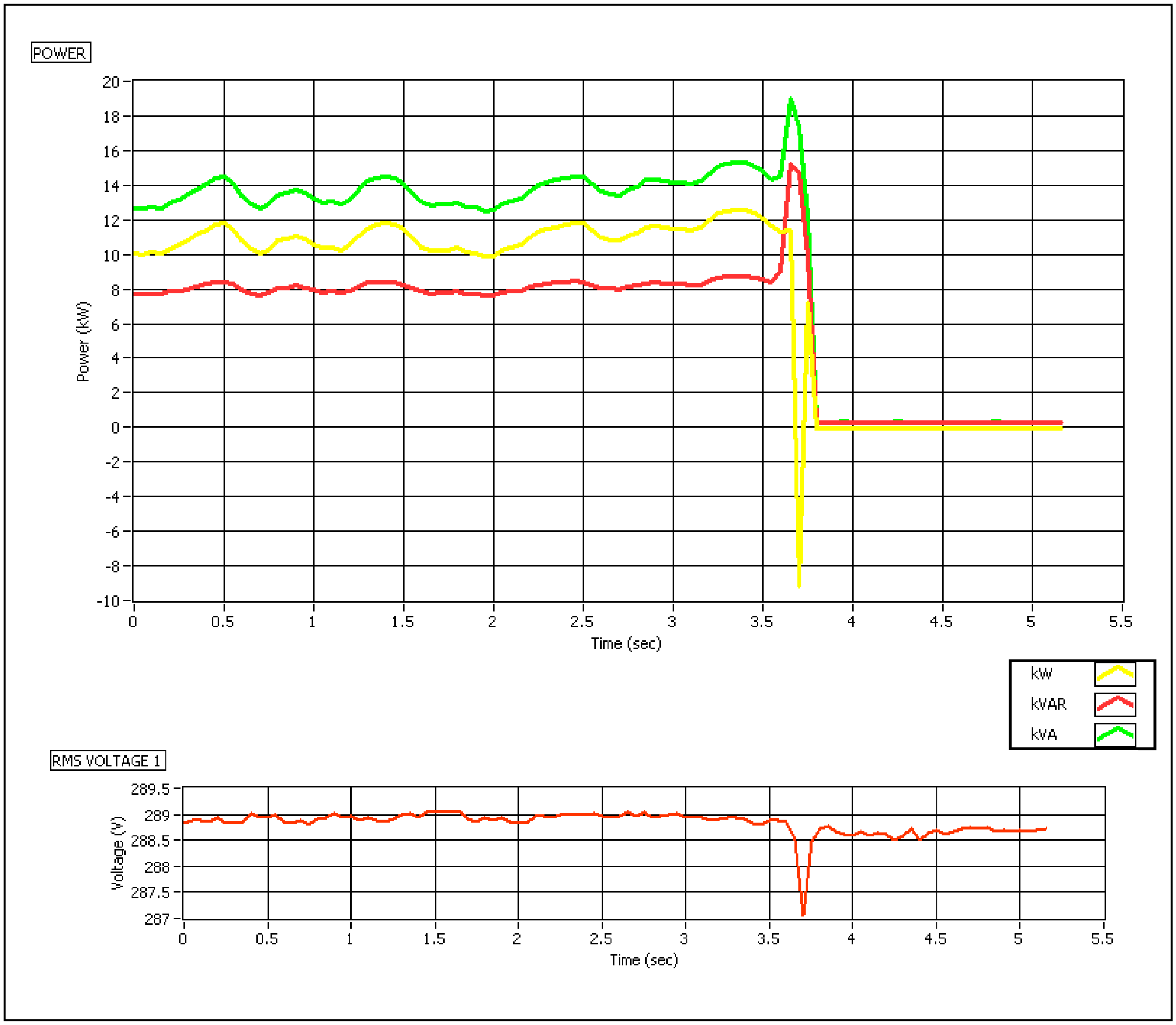


Figure 19: Rated wind (10.0 m/s) stop: power and RMS voltage (December 31, 2009)

The maximum number of switching operations for 10-min and 120-min intervals (N_{10} and N_{120}) for each type of switching operation was not provided by the turbine manufacturer. So, the N_{10} and N_{120} values were assumed based on the method given by IEC61400-21. The flicker step factor and voltage change factors were determined as the average results of five values are shown in the tables below.

Table 12. Characteristics of start at cut-in wind speed

Case of switching operation:	***Start at cut-in wind speed***			
Maximum number of switching operations, N_{10}:	10			
Maximum number of switching operations, N_{120}:	120			
Network impedance angle, Ψ_k	*30°*	*50°*	*70°*	*85°*
Flicker step factor, $k_f(\Psi_k)$:	4.165	4.956	5.128	4.856
Voltage change factor, $k_U(\Psi_k)$:	0.095	0.071	0.049	0.056

Table 13. Characteristics of stop at cut-in wind speed

Case of switching operation:	***Stop at cut-in wind speed***			
Maximum number of switching operations, N_{10}:	10			
Maximum number of switching operations, N_{120}:	120			
Network impedance angle, Ψ_k	*30°*	*50°*	*70°*	*85°*
Flicker step factor, $k_f(\Psi_k)$:	1.167	1.067	0.892	0.753
Voltage change factor, $k_U(\Psi_k)$:	0.029	0.039	0.048	0.048

Table 14. Characteristics of start at rated wind speed

Case of switching operation:	***Start at rated wind speed***			
Maximum number of switching operations, N_{10}:	1			
Maximum number of switching operations, N_{120}:	12			
Network impedance angle, Ψ_k	*30°*	*50°*	*70°*	*85°*
Flicker step factor, $k_f(\Psi_k)$:	4.100	4.851	5.022	4.773
Voltage change factor, $k_U(\Psi_k)$:	0.082	0.064	0.051	0.066

Table 15. Characteristics of stop at rated wind speed

Case of switching operation:	***Stop at rated wind speed***			
Maximum number of switching operations, N_{10}:	1			
Maximum number of switching operations, N_{120}:	12			
Network impedance angle, Ψ_k	*30°*	*50°*	*70°*	*85°*
Flicker step factor, $k_f(\Psi_k)$:	1.544	1.171	1.001	1.046
Voltage change factor, $k_U(\Psi_k)$:	0.056	0.062	0.066	0.067

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 above tables by applying linear interpolation.

5.0 Exceptions

Exceptions to IEC61400-21:

- The current and voltage sensors used for this testing do not meet the Standard requirements for compliance with the IEC 60044-1 and IEC 60186 respectively, but they do exceed the minimum accuracy required by the Standard. This should have no effect on results or uncertainty.
- The 15 m/s wind speed bin was not filled because it is difficult for our site to have high wind speed within the 8% to 16% turbulence intensity required in the standard due to our diverse terrain.

Appendix A. Test Matrix

Test Type	Measured	Required by IEC 61400-21 and MEASNET
Continuous operation: number of 10 min intervals	5 for each bin, except 15 m/s bin	At least 5 for each 1 m/s wind speed bin
Switching operation: number of wind turbine starts (cut-in wind speed)	5	At least 5
Switching operation: number of wind turbine stops (cut-in wind speed)	5	At least 5
Switching operation: number of wind turbine starts (rated wind speed)	5	At least 5
Switching operation: number of wind turbine stops (rated wind speed)	5	At least 5

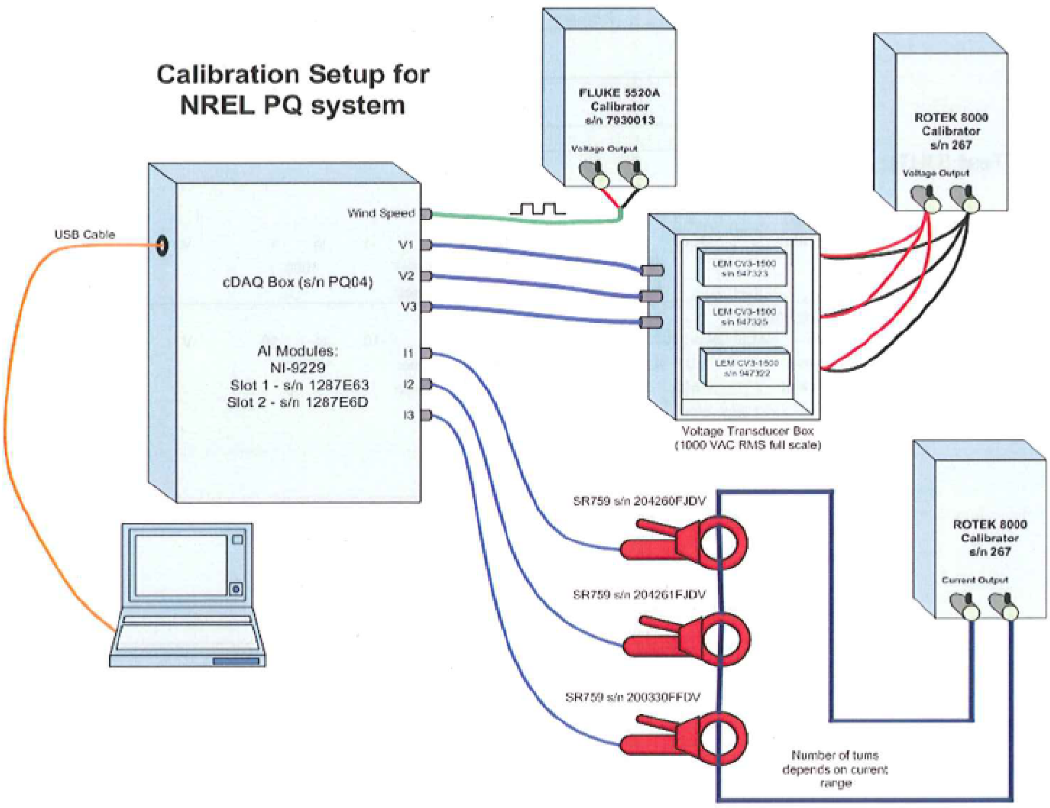
Appendix B. Post Calibration Report

National Renewable Energy Laboratory

Calibration Report

Report #: NREL PQ Sampling System Cal (sn PQ04) 100125

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: 1/25/10
Calibration Due Date: 1/25/11
NREL Metrology Laboratory: Ibrahim Reda
Senior Scientist-II
Date: 1/28/2010

1/28/2010 PQ Sampling System Cal Report (sn PQ04) 100125.xls Page 1 of 6

Calibration Standard:

Rotek Current Calibrator

Model: 8000A		**Calibration Date:**	7/29/05
Serial # : 267		**Calibration Due Date:**	7/29/06
DOE Tag: 126314			

Fluke Voltage Calibrator

Model: 5520A		**Calibration Date:**	8/3/05
Serial # : 7930013		**Calibration Due Date:**	8/3/06
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: SR759

Accuracy: 0.3 % of F.S.

Full scale: -100 100 A **Output:** -1 to 1 V

Nominal Slope: 100

Nominal Offset: 0

Voltage sensors

Model: LEM CV 3-1500 **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: NI 9127

Filter cut-off: 25 kHz

A/D Converter

Model: NI-9233

Combined accuracy of A/D Converter: 0.02 % of F.S.

Uncertainty of UUT:

Current Total Uncertainty = **0.30 A**

Voltage Total Uncertainty = **3.01 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

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	0.000	0.02	0.000	0.01	0.002	0.19	30
2	Yes	0.020	0.01	0.020	0.01	0.020	-0.01	28
4	Yes	0.040	0.01	0.040	0.01	0.040	-0.01	26
6	Yes	0.060	0.01	0.060	0.00	0.060	-0.02	25
8	Yes	0.080	0.00	0.080	0.00	0.080	-0.02	23
10	Yes	0.100	0.00	0.100	-0.01	0.100	-0.02	22
12	Yes	0.120	-0.01	0.120	-0.01	0.120	-0.02	21
14	Yes	0.140	-0.01	0.140	-0.01	0.140	-0.02	20
16	Yes	0.160	-0.01	0.160	-0.02	0.160	-0.03	19
18	Yes	0.180	-0.02	0.180	-0.02	0.180	-0.03	18
20	Yes	0.200	-0.02	0.200	-0.03	0.200	-0.03	17
30	Yes	0.3	-0.04	0.301	0.05	0.3	-0.04	14
40	Yes	0.401	0.05	0.401	0.03	0.4	-0.05	12
50	Yes	0.501	0.03	0.501	0.01	0.501	0.04	11
60	Yes	0.601	0.01	0.601	-0.01	0.601	0.03	10
70	Yes	0.701	-0.01	0.701	-0.03	0.701	0.02	9
80	Yes	0.801	-0.02	0.801	-0.05	0.801	0.01	8
90	Yes	0.901	-0.04	0.902	0.03	0.901	0.00	7
100	Yes	1.002	0.04	1.002	0.01	1.001	-0.01	7
	Calculated slope and offset:							TUR is always >4
	Slope:	99.83		99.80		99.90		
	Offset:	0.0156183		0.01464		-0.0092		

Frequency Measurements

Fluke 5520A	Within	Unit under test	
Frequency	Tolerance?	Wind Speed Input	
Hz		Hz	Error, Hz
100	Yes	100.000	-0.01
200	Yes	199.999	-0.01
300	Yes	300.009	0.00
400	Yes	400.009	0.01
500	Yes	500.004	0.00
600	Yes	600.006	0.00
800	Yes	800.008	0.01
1000	Yes	999.988	-0.01
	Calculated slope and offset:		
	Slope:	1.00	
	Offset:	-0.0067166	

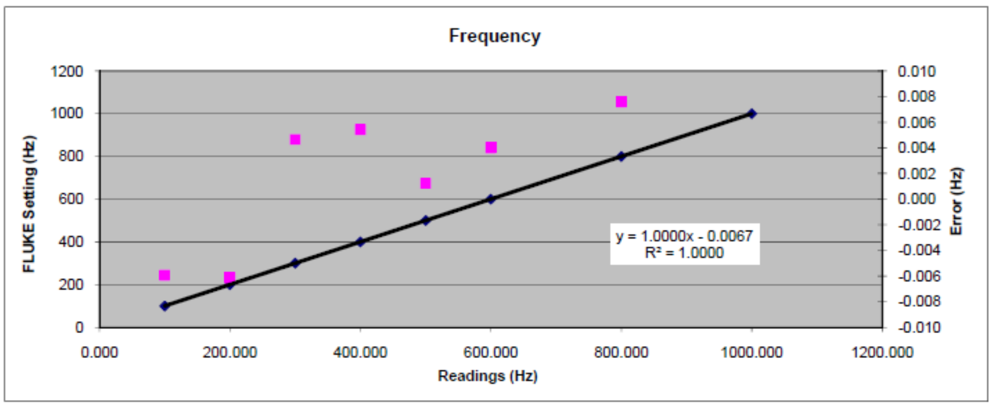
Voltage Measurements

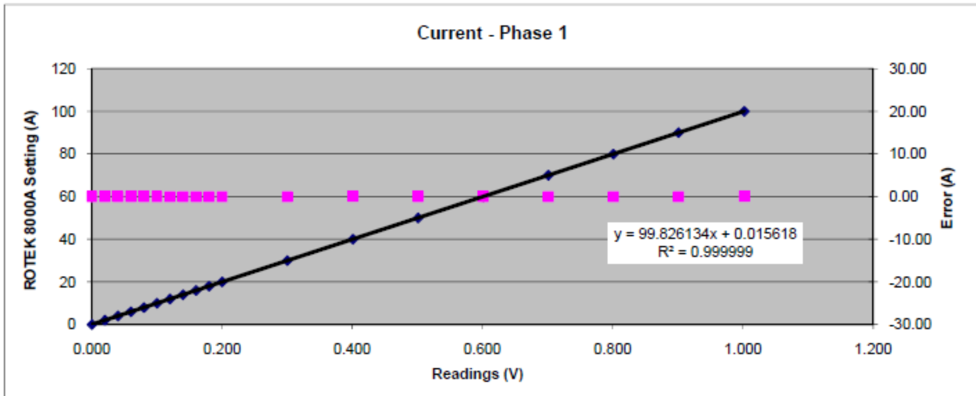
Line-to-neutral or line-to-ground measurements

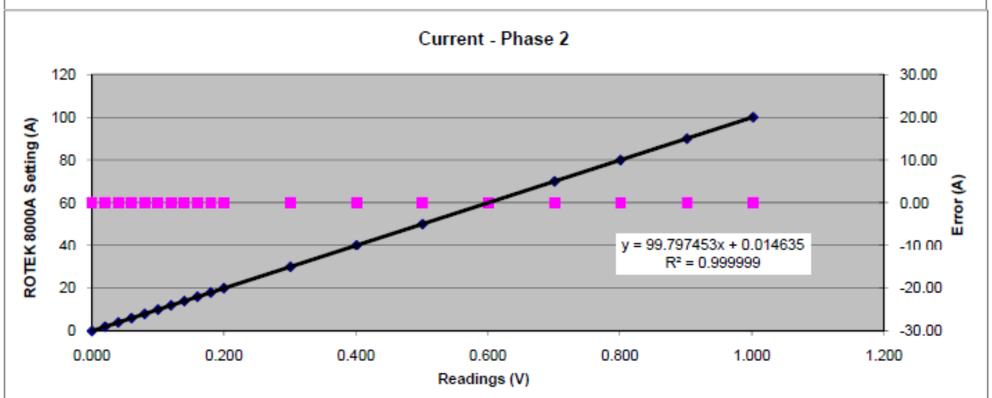
ROTEK 8000A	Within	Unit Under Test						
RMS Voltage	Tolerance?	Phase 1		Phase 2		Phase 3		TUR
V		V	Error, V	V	Error, V	V	Error, V	
240	Yes	1.6	-0.03	1.6	-0.03	1.601	0.03	31
250	Yes	1.667	0.01	1.667	0.01	1.668	0.07	30
260	Yes	1.734	0.06	1.734	0.06	1.734	-0.04	29
270	Yes	1.8	-0.05	1.8	-0.05	1.801	0.00	28
277	Yes	1.847	0.00	1.847	0.00	1.847	-0.10	27
280	Yes	1.867	0.00	1.867	0.00	1.868	0.04	27
290	Yes	1.934	0.04	1.934	0.04	1.934	-0.06	26
300	Yes	2	-0.06	2	-0.06	2.001	-0.02	26
310	Yes	2.067	-0.02	2.067	-0.02	2.068	0.02	25
320	Yes	2.134	0.03	2.134	0.03	2.135	0.06	24

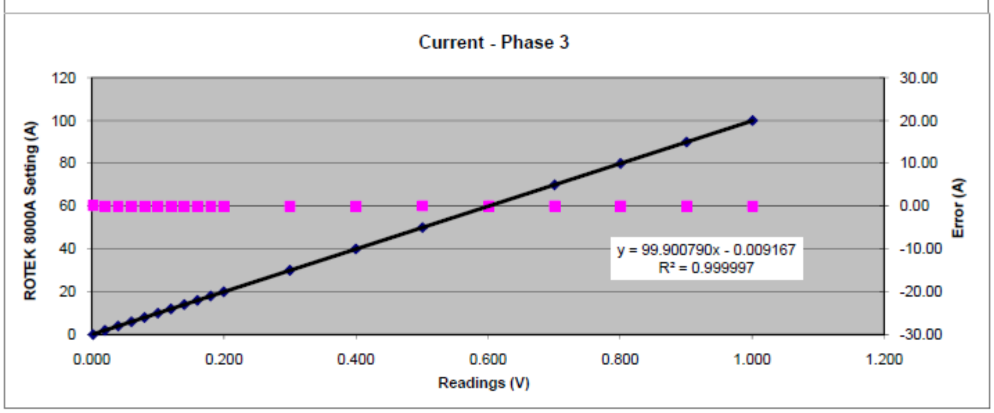
Calculated slope and offset: **TUR is always >4**

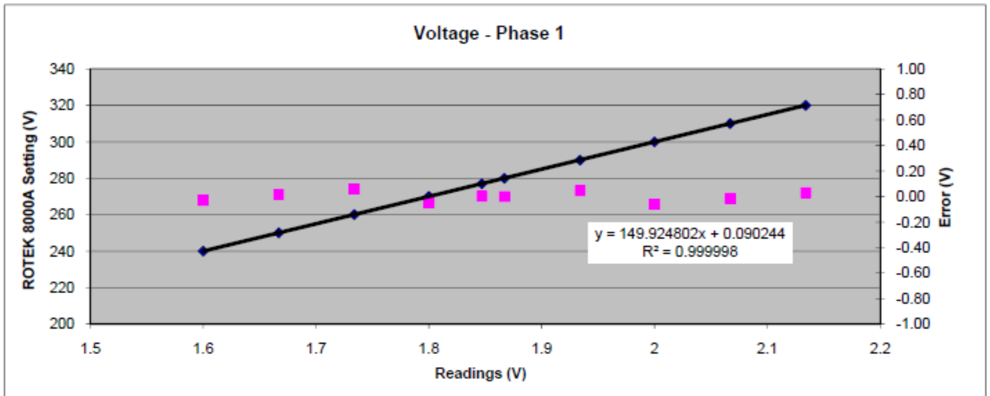
	Phase 1	Phase 2	Phase 3
Slope:	149.92	149.92	149.88
Offset:	0.0902444	0.09024	0.07042



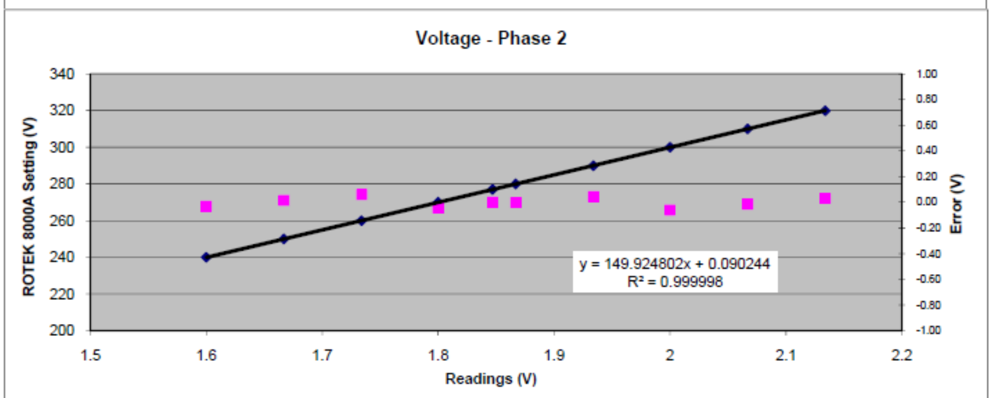

Current - Phase 1
ROTEK 8000A Setting (A)
Error (A)
Readings (V)
y = 99.826134x + 0.015618
R² = 0.999999


Current - Phase 2
ROTEK 8000A Setting (A)
Error (A)
Readings (V)
y = 99.797453x + 0.014635
R² = 0.999999

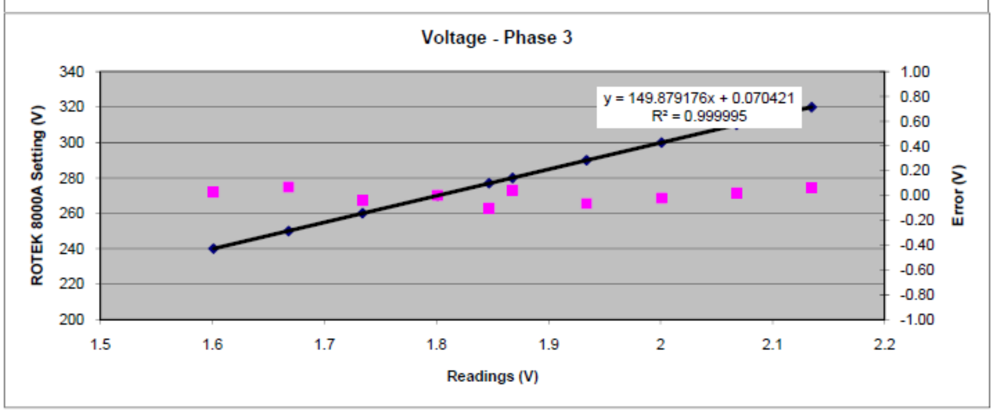

Current - Phase 3
ROTEK 8000A Setting (A)
Error (A)
Readings (V)
y = 99.900790x - 0.009167
R² = 0.999997



Voltage - Phase 1
ROTEK 8000A Setting (V)
Error (V)
Readings (V)
y = 149.924802x + 0.090244
R² = 0.999998



Voltage - Phase 2
ROTEK 8000A Setting (V)
Error (V)
Readings (V)
y = 149.924802x + 0.090244
R² = 0.999998



Voltage - Phase 3
ROTEK 8000A Setting (V)
Error (V)
Readings (V)
y = 149.879176x + 0.070421
R² = 0.999995