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SURVEY OF POWER CURVES FOR SMALL WIND TURBINES BASED ON IEC 61400-12-1

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Abstract. *This work presents wind turbine power curves for a small wind turbines. The power curves were generated in the real operational conditions. The international standard IEC 61400-12-1 for small wind turbines is employed in this paper. This standard is usually used for the certification of wind turbines. Wind turbine manufacturers usually provide in their sales brochure the power performance curve, although it is not always possible to rely on such sales or marketing gimmicks. This work uses raw wind data from an open field at the Federal Institute of Pernambuco (IFPE) - Campus Ipojuca. The data was processed and analyzed by the Visual Basic in the Excel's tool. The results show a significant difference between the power curve from the wind turbine manufacturer and the measured curve. This work also analyzes the possible reasons of this discrepancy.*

Keywords: *Certification, IEC, Power Curve, Small wind turbine, PILACAS.*

1. INTRODUCTION

The world market for small wind turbine is growing steadily. By the end of 2012, a total of 806,000 (cumulative) small wind turbines have been installed all over the world, which was almost an of increase of 10 % compared to the previous year. However, most of the growth happened in three countries: China, USA and UK (Gsänger and Pitteloud, 2014).

In the United States and in Europe, it is estimated that 25% or more number of small wind turbines (50 – 300 W) are connected to the electric grid. China, the largest manufacturer of small wind turbines in the world, a large proportion of these turbines are for domestic use as a stand-alone system (Nelson, 2009). The major countries of European Union (France, Germany, Italy, Spain and The Netherlands) represents, approximately, 70% of the total installed wind power, i.e. 106 GW (Bortolini *et al*., 2014).

There is a good promise for micro-generation (up to 100 kW) and mini-generation (100 to 1000 kW) (ANEEL, 2015) in Brazil. However, due to the absence of detailed information on small wind turbines, the Ministry of Mines and Energy (MME) requested to the Center of Electric Energy Institute (CEPEL) to make a report on small wind turbines - utilization, cost, certification and application in the country. Other aspects of the report also included the utilization by consumers of electricity from the Sistema de Compensação Energética vide regulation number 482/2012 of ANEEL by which the consumer can get credit for the excess energy inserted into the grid (CEPEL, 2014; Juárez *et al*., 2014; Araújo *et al*., 2013).

The ANEEL organized a public hearing on 17 and 18 June, 2015 to discuss the proposal of the Regulation Number 482/2012. The objective of this public hearing was to minimize the existing barriers faced by the micro- and mini-generation to the grid; make compatible rules for the payment of electric energy with the General Conditions of Delivery; create more interest to the public and, also, improve the regulation. To provide incentives in this end, at present only five states (São Paulo, Pernambuco, Minas Gerais, Goiás, and Rio Grande do Norte) provide the exemption of sales and service taxes (ICMS) (ANEEL, 2015).

According to the ANEEL, there are less than 20 registered residential customers that have installed micro-generation (wind turbines). It seems that this low number is associated with the bureaucratic setup and a high cost of implementing the technology (Jornal do Commércio, 2015; ANEEL, 2015; R7, 2015).

The process of certification of a small wind turbine is aimed to verify if the turbine specifications are matched to the real working conditions (Manwell *et al.*, 2009). One of the most important specification is verification of the power curve, which is usually done according to the standards of International Electrotechnical Commission, IEC 61400-12-1 (Whale, 2013; da Silva, 2014; Moura, 2014). Figure 1 illustrates this procedure.

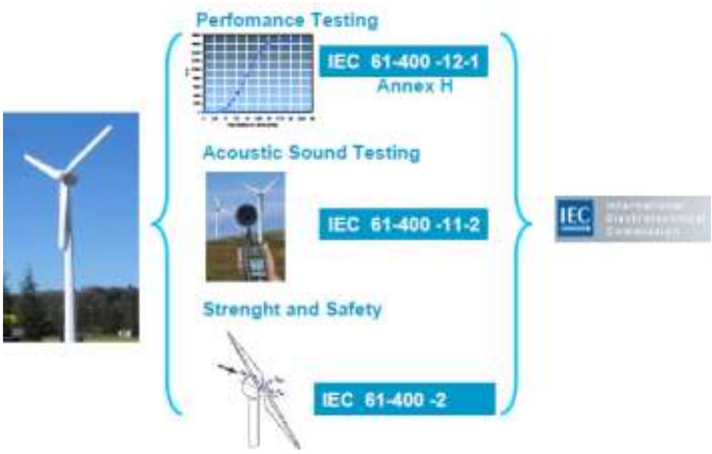

Figure 1. Tests for certification of a wind turbine (Alé, 2012).

The wind turbine manufacturers always provide power curve for their turbines, however it is not always possible to accept their accuracy. This paper makes an attempt to analyze the power curve of a small wind turbine: GERAR 246 according to the standards of IEC 61400-12-1 (da Silva, 2014). The verification was realized in an open site at the Campus of the Federal Institute of Pernambuco (IFPE) at Ipojuca and with the help of Federal University of Pernambuco (UFPE) under the auspices of project called PILACAS (Mecânica dos Fluidos Ambiental, 2014)

2. METHODOLOGY

The methodology utilized in this study uses the three variables from the wind turbine, i.e., voltage, current anf frequency by a specially designed transducer. And from the wind data acquisition system on the meteorological were measured pressure, temperature, direction and wind speed at rate of 1 Hz, The power curve is determined by the method of the bins for the normalized data using bins of 0.5 m/s as per the standard IEC 61400-12-1 (2005). that is, by calculating the average speed and electric power output, both normalized to each bin speed. The IEC standard Annex H also specifies that the speed range should be from 1 m/s through 14 m/s. The construction of the power curve basically consists of three steps:

a) collection and processing of data;
b) power calculation;
c) surveying the power curve and uncertainties.

2.1 Collection and processing of data

The collection starts from the datalogger. Data are collected at a frequency of 1 Hz and subsequently obtained average of 1 min as established in IEC for small wind turbines in Annex H of this standard. These data are stored on a memory card inserted into the datalogger in .DAT format and then converted to a .txt format easier to handle through the LoggerNet® software. The data in .txt format is imported into Excel®. Because of the interaction of turbine as an obstacle influences data collected, it is necessary to exclude some sectors whose wind speed measurement is disturbed. The database validation occurs by measuring exclusion of these sectors as given by the equation:

$$\alpha = 1.3\,a\tan\left(\frac{2.5D_n}{L_n} + 0.15\right) + 10 \tag{1}$$

where,

D_n - is the diameter of wind turbine
L_n - is the distance between the turbine tower and the meteorological tower

2.2 Power calculation

The normalized total power in the bin *i* considering a system with balanced current and respective phase voltage is expressed:

$$P_n = \sqrt{3}\, U_i \ I_i \ \frac{\rho_0}{\rho_i} \tag{2}$$

where,
U_i - is the average voltage of bin *i*
I_i - is the average current of bin *i*
ρ_i - is the average density of bin *i*
ρ_0 - is the air standard density (1.225 kg/m³)

2.3 Surveying the power curve and uncertainties

According to the ISO Guide, there are two types of uncertainties: Type A, which can be deduced from the measurements and Type B, which are estimated by other means. The combined power uncertainty in a bin *i* is expressed:

$$u_{cP,i} = \sqrt{3\left[\left(I_i \ u_{cU,i} \right)^2 + \left(U_i \ u_{cI,i} \right)^2 \right]} \tag{4}$$

where,
$u_{cP\ i}$ - combined uncertainty of electric power in bin *i*
$u_{cI,i}$ - combined uncertainty of current transducer in bin *i*
$u_{cU,i}$ - combined uncertainty of voltage transducer in bin *i*

The combined standard uncertainty of each bin of the power curve are found by combining the uncertainty category A with all the uncertainties of category B and is expressed:

$$u_{c,i} = \sqrt{u_{cP,i}^2 + c_{V,i}^2 \ u_{V,i}^2 + c_{T,i}^2 \ u_{T,i}^2 + c_{B,i}^2 \ u_{B,i}^2} \tag{5}$$

where,
$c_{V,i}$ - sensitivity factor for the speed
$u_{V,i}$ - uncertainty at each wind speed bin
$c_{T,i}$ - sensitivity factor for the temperature
$u_{T,i}$ - uncertainty at each temperature bin
$c_{B,i}$ - sensitivity factor for the pressure
$u_{B,i}$ - uncertainty at each pressure bin

The power coefficient is calculated:

$$C_{P,i} = \frac{P_i}{\frac{1}{2}\rho_0 A V_i^3} \tag{6}$$

where,
$C_{P,i}$ - power coefficient for bin *i*
V_i - is the average speed for bin *i*
P_i - is the average power in bin *i*
A - is the rotor swept area

3. RESULTS AND DISCUSSION

The rotor diameter (*D*) of the wind turbine in this study is 2.46 m. The distance between the two towers was 3.25*D*. Substituting these data in the Eq. (1), it is estimated that the excluded sector is in order of 66°. As the meteorology towers are located in the North (geographic) in relation to the turbine, the excluded sector would lie in the range 327° and 33°, see Fig. 2.

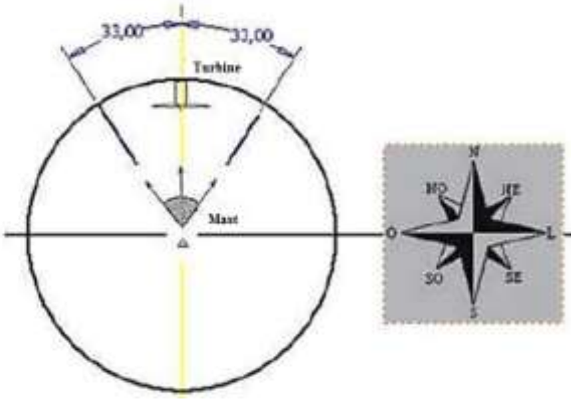

Figure 2. Excluded sectors in the data assessment.

The total number of raw data collected at the rate of 1 Hz were 1,734,321. Out of this total, about 26% of data were excluded either due to empty cells or due to invalid measurements, thereby resulting into 1,279,812 valid data.

From Eq. (5) is estimated combined uncertainties for the power curve for each bin, Tab. 1.

Table 1. Combined uncertainty in power curve.

Bin nº i	Hub Height Wind Speed V_i m/s	Category B Uncertainty Power Output $u_{cP,i}$ W	Category B Uncertainty Wind Speed $u_{V,i}$ m/s	Wind Speed $c_{V,i}*u_{V,i}$ W	Category B Uncertainty Air Temperature $u_{T,i}$ K	Air Temperature $c_{T,i}*u_{T,i}$ W	Category B Uncertainty Air Pressure kW/hPa $u_{B,i}$ Pa	Air Pressure $c_{B,i}*u_{B,i}$ W	Combined Standard Uncertainty uc,i kW
1	0.58	0.00173	0.112	0.00102	2.1	0.00000	300	0.00000	0.0
2	1.05	0.00087	0.116	0.00093	2.1	0.00000	300	0.00000	0.0
3	1.53	0.00112	0.121	0.00450	2.1	0.00000	300	0.00000	0.0
4	2.02	0.00175	0.129	0.01263	2.1	0.00000	300	0.00000	0.0
5	2.52	0.00403	0.138	0.03079	2.1	0.00000	300	0.00000	0.0
6	3.01	0.01095	0.149	0.09491	2.1	0.00000	300	0.00000	0.1
7	3.50	0.04258	0.160	0.34451	2.1	0.00001	300	0.00000	0.3
8	3.99	0.19582	0.171	2.21684	2.1	0.00006	300	0.00002	2.2
9	4.48	0.54042	0.184	8.78675	2.1	0.00023	300	0.00009	8.8
10	5.00	0.65713	0.197	13.63188	2.1	0.00049	300	0.00020	13.6
11	5.49	0.75545	0.211	11.62848	2.1	0.00069	300	0.00028	11.7
12	6.00	1.11457	0.225	17.54293	2.1	0.00097	300	0.00039	17.6
13	6.49	1.70302	0.239	31.25244	2.1	0.00145	300	0.00059	31.3
14	6.99	2.11023	0.253	36.47471	2.1	0.00197	300	0.00080	36.5
15	7.49	2.33758	0.268	25.46268	2.1	0.00231	300	0.00094	25.6
16	8.00	2.53762	0.283	18.16542	2.1	0.00255	300	0.00104	18.3
17	8.49	2.75917	0.298	16.92699	2.1	0.00275	300	0.00112	17.2
18	8.98	2.96327	0.312	16.59835	2.1	0.00295	300	0.00120	16.9
19	9.47	3.17494	0.327	16.57777	2.1	0.00312	300	0.00127	16.9
20	9.98	3.41952	0.343	17.71336	2.1	0.00332	300	0.00135	18.0
21	10.44	3.73385	0.357	16.91079	2.1	0.00348	300	0.00141	17.3
22	10.97	4.26595	0.373	14.87720	2.1	0.00363	300	0.00148	15.5
23	11.45	5.82268	0.388	28.57048	2.1	0.00389	300	0.00158	29.2
24	11.98	3.80663	0.404	3.74707	2.1	0.00392	300	0.00159	5.3

Table 2 presents performance of wind turbine GERAR 246. The bins 23 and 24 does not conform to the standard Annex H, IEC 61400-12-1. Note that this standard recommends to use mean wind speeds for an interval of 1-minute instead of 10-minutes as used for the large wind turbines. However, it is noted that in Fig. 3 that there is no significant difference between the power curves obtained, i.e., wind speeds (measured at 1-min and 10-min) interval.

Table 2. Combined Uncertainty, Power Coefficient and Power output.

Standard air density: 1.225 kg/m^3					**Combined Uncertainty**
Bin nº	**Hub Height Wind speed (m/s)**	**Power output W**	**C_p**	**Nº of data set**	**Standard Uncertainty u_{ci} kW**
1	0.5	0.01	0.01	44	0.00
2	1	0.01	0.00	239	0.00
3	1.5	0.03	0.00	590	0.00
4	2	0.07	0.00	1250	0.01
5	2.5	0.19	0.00	1752	0.03
6	3	0.50	0.01	2421	0.10
7	3.5	1.56	0.01	2733	0.35
8	4	7.89	0.04	2500	2.23
9	4.5	31.47	0.12	1742	8.80
10	5	66.71	0.18	1445	13.65
11	5.5	94.20	0.20	1324	11.65
12	6	133.35	0.21	1207	17.58
13	6.5	198.32	0.25	1054	31.30
14	7	270.26	0.27	804	36.54
15	7.5	317.11	0.26	681	25.57
16	8	349.95	0.24	563	18.34
17	8.5	378.00	0.21	389	17.15
18	9	404.29	0.19	249	16.86
19	9.5	428.65	0.17	155	16.88
20	10	455.16	0.16	107	18.04
21	10.5	477.01	0.14	51	17.32
22	11	498.11	0.13	23	15.48
23	11.5	533.36	0.12	6	29.16
24	12	538.34	0.11	1	5.34

Figure 3 shows the comparison of the calculated and manufacturer's power curves. The difference between the manufacturer's power curve and the tested power curves (both the curves: 1 minute and 10 minutes) is quite large when the wind speed is 7 m/s or more. Going back to the Tab. 2, it is noted that the number of data reduce faster when the wind speed reaches 7 m/s or more which results into higher levels of uncertainties. The simple reason for these uncertainties is that for the test site in this region of trade winds, the occurrences of wind speed in excess of 7 m/s is quite infrequent. This fact is illustrated in Fig. 4.

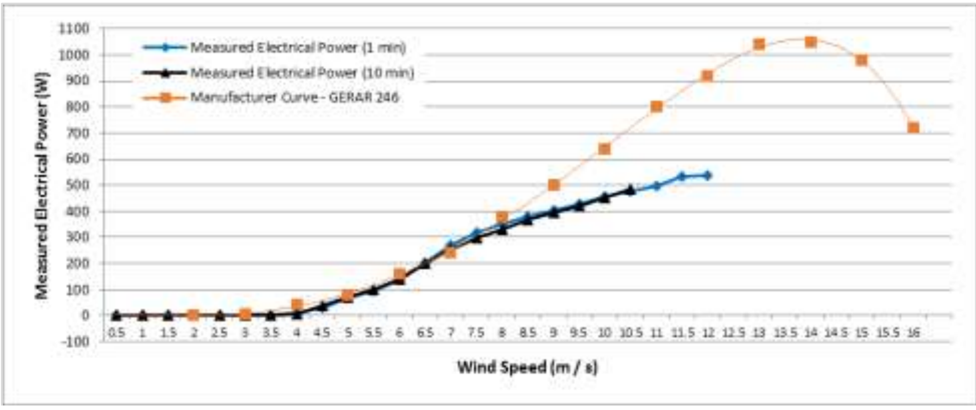

Figure 3. Power curve for wind turbine GERAR 246.

Figure 4 shows Wind speed frequency histogram. It is observed that wind speed of about 3.5 m/s occurs 13%, which is approximately the cut-in speed of the turbine. Whereas wind speed of 7 m/s blows not more than 4% of the time (equivalent to about 350 hours in a year).

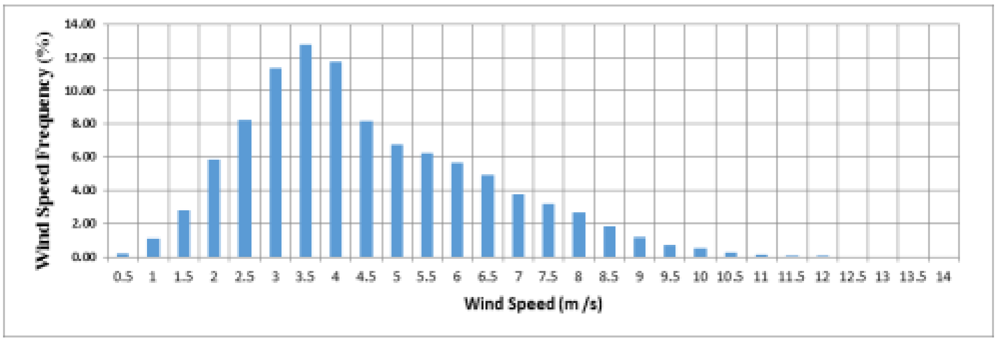

Figure 4. Wind speed frequency.

Figure 5 shows variation of power coefficient of the wind turbine. It is seen that the maximum power coefficient of about 0.27 is obtained at the wind speed of 7 m/s estimated by Eq. (6).

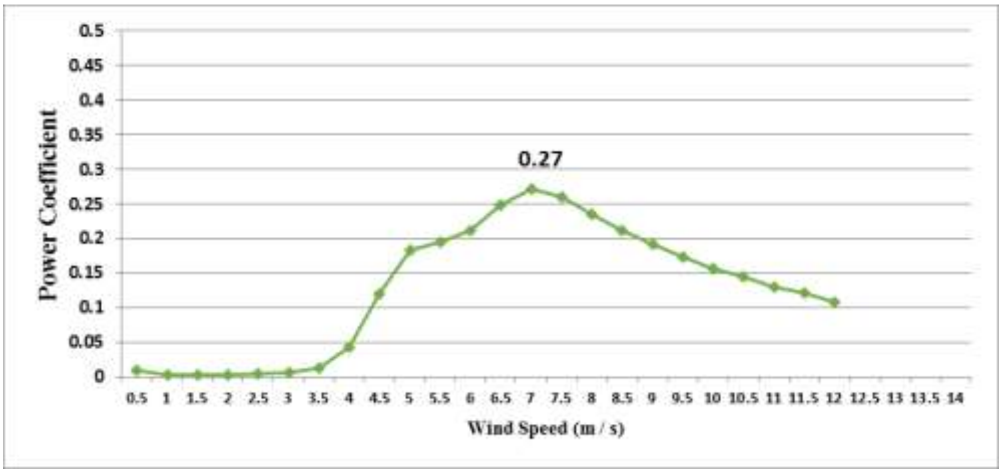

Figure 5. Power coefficient of the wind turbine GERAR 246.

Figure 6 shows the power scatter curves: minimum, maximum and mean values versus wind speeds taken from 1-min intervals. It also shows standard deviations. It is noted that at higher wind speeds, 6 m/s to 9 m/s, there are high incidence of scattering as well as of higher scattering of standard deviation. Also, it is seen that the mean dispersion follows the similar trend as was shown in Fig. 3.

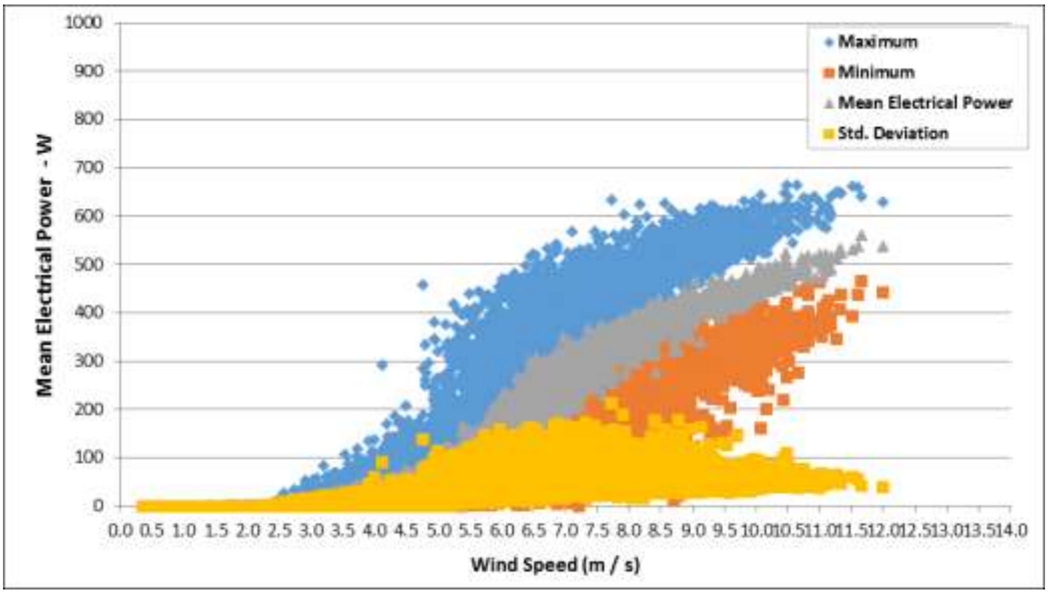

Figure 6. Scatter plot of power output.

4. CONCLUSIONS

The results show a significant difference between the wind turbine manufacturer's power curve and the calculated power curves. It is seen that when the wind speed is in excess of 7 m/s there is a significant difference of power coefficient. Also, the maximum power coefficient is obtained when the wind speed is about 7 m/s. According to the authors, the reason for this discrepancy in the power curves could be attributed to the fact that the small sized wind turbine manufacturers' test the turbine in the laboratory settings where an electric motor drives the generator at different speed settings, simulating the variation in wind speeds. Another factor that could be attributed to the differences in the power curves (to a lesser extent) is that there are infrequent occurrences of wind speed in excess of about 7 m/s. Another important conclusion that it is observed is that the IEC standard recommends mean wind speed interval for small wind turbine of 1-min, however it is observed in this paper that 10-min interval are reasonable even for small wind turbines.

5. ACKNOWLEDGEMENTS

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