Wind Farm Power Performance Test, in the scope of the IEC 61400-12.3

Helder Carvalho[1] (helder.carvalho@megajoule.pt)
Miguel Gaião[2] (miguel.gaiao@edp.pt)
Ricardo Guedes[1] (ricardo.guedes@megajoule.pt)

[1] Megajoule, Renewable Energy Consultants (www.megajoule.pt)
[2] EDP Renováveis, SA (www.edp.pt)

Abstract

The IEC 61400-12.3 technical guideline will define directives on how to correlate local climate and wind farm production statistics to obtain an overall wind farm power curve, or performance matrix. The process is expected to be called Wind Farm Power Performance Test.

These guidelines are being discussed in a recently created IEC working group. They will represent a major aid in independent evaluation of wind farm performance over time, assessment of production ability against estimates or warranties, in providing binding information for buyers or loaners or even simulate the impact of wind farms on electrical grids.

The authors have considered a possible approach to this Wind Farm Power Performance Test, based on a Performance Matrix (PM).

This approach was tested in a real case Wind Farm - Fonte da Mesa Wind Farm located in Portugal on a mountainous complex site. This wind farm started working in 1996 and the owner is EDP Renováveis, SA.

The use of the PM to estimate Wind Farm production was tested using real wind data and comparing results with actual production. Results were quite encouraging, with an average deviation of only 3%.

The sensitivity of results to aspects like length of local data, wind direction discretization, air density correction, day/night and seasonal variations were tested. The results showed a high consistency.

While these first tests were very interesting, tests on other wind farms are necessary to better assess this approach and, namely, tests for larger wind farms, non complex sites, impact of turbulence, wakes, blockage effects on measurements and procedures for more than one wind measurement site.

Keywords: Power Performance Test, Performance Matrix, IEC 61400-12, Power Curves

1. Introduction

It is obvious that wind farm production will be correlated with local climate. Depending on the consistency and stability of this correlation, this can be used to describe the energy production behavior of a Wind Farm (WF) as a Power Curve is used to describe a Wind Turbine. The correlation between local wind and wind farm production can help to monitor performance over time, assessment of production ability against estimates or warranties and provide binding information for buyers or loaners

While this is not an original idea, the fact is that little work is known on this matter. A recent IEC working group is tasked to develop a new guideline (the IEC 61400-12.3) which will define procedures to measure Wind Farm Performance as a function of wind measurements in one, or more, reference sites.

This paper introduces a possible approach, based on a Wind Farm Performance Matrix concept (PM). The authors have tested the procedure in a real WF and using real production and wind data.

The PM consistency was tested against several factors like length of PM Database and test datasets, wind direction discretization, air density correction, day/night and seasonal.

2. Wind Farm Performance Matrix

The relationship between WF active power output (P) and the reference site wind observations, mainly wind speed (U), direction (D) and air density (ρ) can be represented by a Wind Farm Performance Matrix (PM).

P is considered to be the active power output metered by the SCADA at the WF Substation (interconnection transformer external side). Energy consumption values could also be taken into consideration.

The process is very similar to that of the determination of a Wind Turbine Power Curve (IEC 61500-12.1, method of bins) and can be compared to determining several WF Power Curves for different wind directions.

For a given wind speed bin i and wind direction bin j the average active power output can be calculated:

$$[1] \quad PM(i,j) = \frac{\sum_{k=1}^{N_{i,j}} P(i,j,k)}{N_{i,j}}$$

where:

PM(i,j) is the average P for U bin i and D bin j dataset;

P(i,j,k) is the observed P for data record k in U bin i and D bin j dataset and

Ni,j is the number of data records in U bin i and D bin j dataset.

If air density correction (normalization) is to be considered, then, in relation with IEC 61400-12.1, U can be corrected as follows, before the binning of the data:

$$[2] \quad U_k^* = U_k \left(\frac{\rho_k}{\rho^{REF}}\right)^{1/3}$$

where:

Uk* is the normalized wind speed for data record k;

Uk is the observed wind speed for data record k;

ρk is the observed air density for data record k and

ρref is the reference air density;

The reference air density is defined by the analyst and should be close to the expected annual average air density of the site.

Depending on the discretization considered for wind speed and wind direction the PM can be represented as something similar to the following table.

Table 1 – Example representation of a WF Performance Matrix

	Dir Bins	**1**	**…**	**12**
Spd Bins	**PM(j,k)**	**345º-30º**	**…**	**315º-245º**
1	**0-1 ms^{-1}**	PM(1,1)	…	PM(1,12)
2	**1-2 ms^{-1}**	PM(2,1)	…	PM(2,12)
…	**…**	…	…	…
30	**29-30 ms^{-1}**	PM(30,1)	…	PM(30,12)

The dataset considered for the construction of the PM, called Database, should be filtered for:

- Invalid or unreasonable observations;
- Malfunction or degradation of measurement equipments and
- Turbine or Wind Farm Unavailability.

Also, the possible influence on wind measurements from nearby wind turbines in terms of wake and blockage effects should be considered carefully.

According to the purpose of the Performance Test, Turbine and WF control (like pitch and grid control) and special operational conditions (like hot or cold climates adjustments, rain, dust, etc…) can also be considered for filtering of the datasets.

3. Wind Farm description

Fonte da Mesa Wind Farm is located near *Lamego*, in Northern of Portugal. The WF is owned by ENERNOVA, from EDP Renováveis (EDP Renewables) Group.

The site is very complex and can be characterized by a hill crest with an orientation NNE - S and with an average altitude of around 950m above sea level.

The WF comprises 17 WECs - Vestas V42 (600kW), with a total installed capacity of 10.2MW. Operation started at late 1996.

The site has 2 monitoring masts (TC1 and TC2), measuring wind speed, direction, temperature and air pressure at rotor height (42 m a.g.l.) and at 10 min. intervals.

Average annual wind climate is predominant from East-Weast quadrants, perpendicular to the turbine row.

Table 2 – Vestas V40 Wind Turbine Description

Model	V42
Hub height	40,5 m
Rotor diameter	42m
Rated power	600 kW
Cut-in wind speed	4 m/s
Nominal wind speed	17 m/s
Cut-out wind speed	25 m/s

Figure 1 – Fonte da Mesa Wind farm

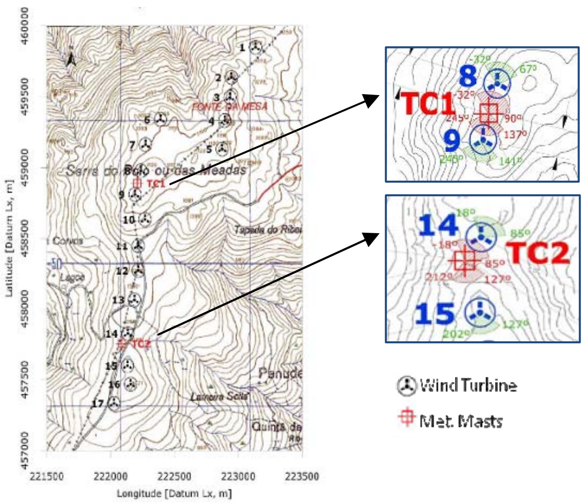

Figure 2- Wind farm layout

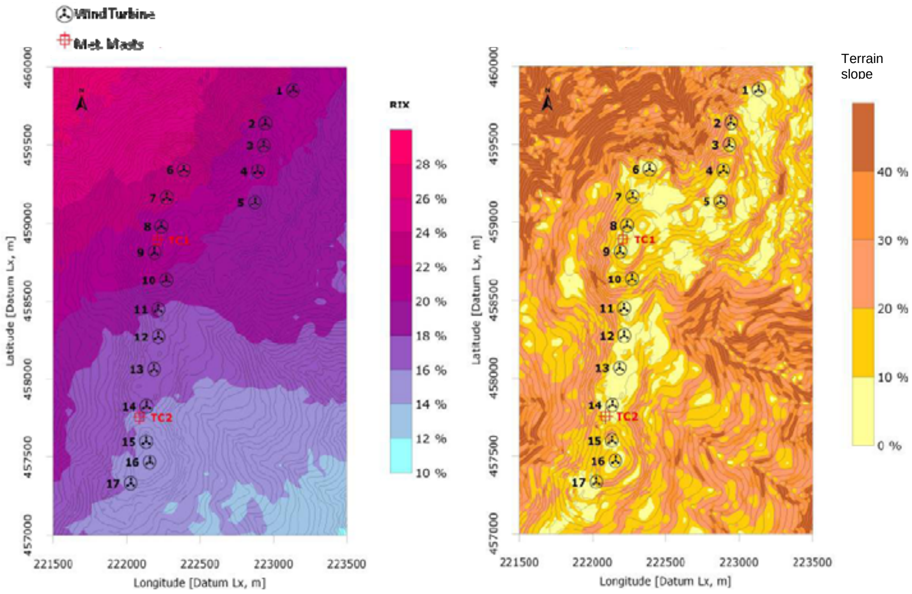

Figure 3 – RIX and terrain slope

Figure 4 – Monitoring Mast

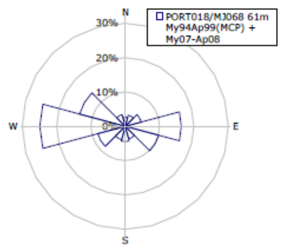

Figure 5- Typical annual Wind Rose for Fonte da Mesa site

4. Wind and Power Datasets

The observations of wind climate and power output for the WF were compiled. All relate to concurrent 10 min. average records recorded by the WF SCADA.

The observations of power output, P, correspond to the measurements the WF Substation (interconnection transformer external side). Wind Farm energy consumption was were not taken into account.

The final recovery rate of the available database is very poor, mainly due to several malfunctions on the monitoring masts. Mast TC2 was disconsidered due to poorer data availability.

Concurrent wind and power data was filtered for Turbine and Wind Farm Unavailability.

The possible disturbance of measurements from nearby WECs on TC1 measurements were not considered or even investigated in detail, as they are within not predominant wind directions.

The final data availability, of both wind, from TC1, and power data is in table 3.

From the available dataset, the years 1998, 1999 and 2002 (3 years) were selected for the PM Database, given the greater data recovery rate and reduced seasonal bias.

Table 3 – Fonte da Mesa Wind and Power Database

Year	Available data (%)
1997	45.6
1998	67.9
1999	76.5
2000	63.9
2001	27.9
2002	77.4
2003	64.4

5. Fonte da Mesa PM

Two approaches were followed for the PM calculation, one disconsidering any air density correction, Regular-PM, and the other considering air density correction, Normalized-PM.

Different widths of wind direction bins were also tested, for 30º, 15º and 5º bins.

The following table and figures show the calculated Regular-PM, for the case of 30º D bins.

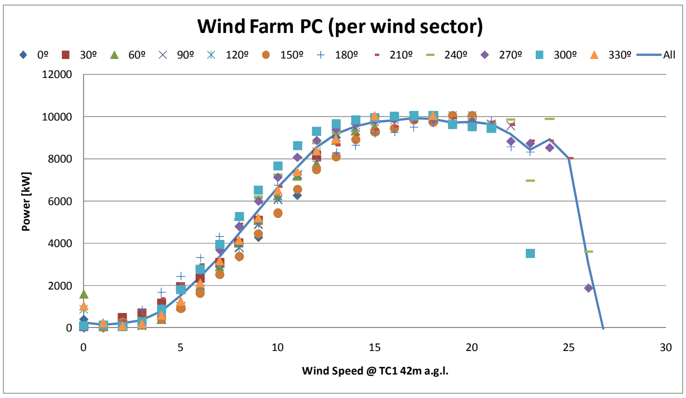

Figure 6 – Wind Farm Power Curves (no air density correction, D bin 30º)

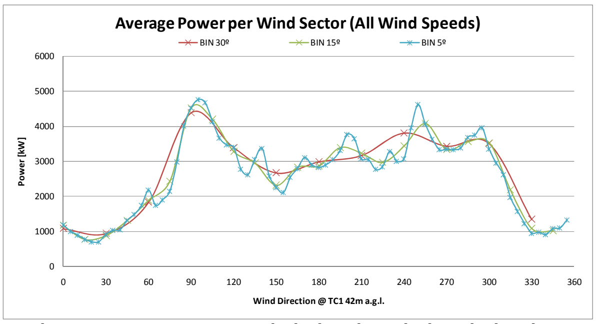

Figure 7 – Average P per Wind Direction Bin (no air density correction, D bin 30º)

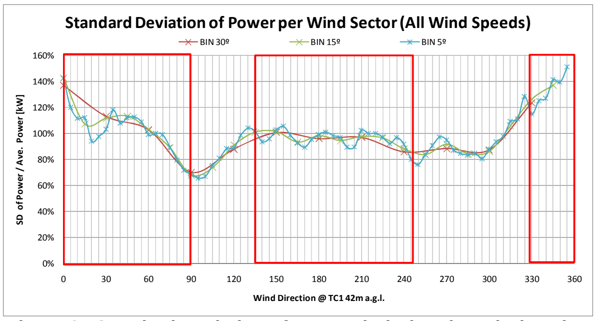

Figure 8 –Standard Deviation of P per Wind Direction Bin (no air density correction, D bin 30º) – red squares represent wind directions for which the mast is behind nearby WECs

Table 3 – Fonte da Mesa PM (no air density correction, D bin 30º)

WD BINS (bin center º)

Power-Mean [kW]	0	30	60	90	120	150	180	210	240	270	300	330	All (average)
0	427	62	1606	56	890	94	58	27	242	0	129	1037	263
1	18	73	72	133	57	41	153	186	114	115	167	237	137
2	93	466	70	81	57	284	305	329	228	115	87	91	212
3	236	706	147	126	92	180	835	672	464	360	285	174	373
4	553	1170	409	413	386	421	1682	1404	1002	962	882	597	802
5	1057	1951	1028	1006	1015	918	2447	2091	1810	1755	1820	1254	1507
6	1845	2340	1934	1828	1799	1660	3307	3017	2859	2697	2786	2120	2400
7	2550	3073	2899	2744	2719	2536	4307	3964	3850	3692	3959	3173	3376
8	3368	4035	4067	3798	3789	3378	5217	4944	5139	4804	5269	4157	4465
9	4298	5079	5112	4895	4907	4465	6095	5966	6210	5996	6531	5209	5556
10	5437	-	6266	6096	6045	5437	6764	6688	7249	7125	7663	6524	6652
11	6282	-	7187	7255	7279	6555	7293	7301	8084	8070	8615	7408	7639
12	8246	8159	7801	8259	8356	7511	7896	7937	8777	8869	9293	8392	8540
13	9018	-	8884	9046	9155	8114	8301	8677	9249	9396	9660	8953	9182
14	-	-	9330	9514	9616	8910	8650	9147	9714	9651	9831	-	9561
15	-	-	9555	9800	9878	9272	9219	9396	9850	9826	9952	10057	9769
16	-	-	-	9982	9867	9466	9266	9541	9922	9866	10001	-	9845
17	-	-	-	10036	10053	9849	9495	9770	9973	9940	10029	-	9951
18	-	-	-	9949	10054	9756	9714	9971	9979	9888	10043	10069	9928
19	-	-	-	9912	10052	10055	9675	9943	9723	9613	9614	-	9723
20	-	-	-	9852	10059	10051	9807	9482	9927	9767	9512	-	9764
21	-	-	-	9663	-	-	9801	9748	9695	9591	9450	-	9662
22	-	-	-	9593	-	-	8577	9637	9864	8825	-	-	9188
23	-	-	-	-	-	-	8341	8879	6988	8731	3545	-	8441
24	-	-	-	-	-	-	-	8869	9919	8525	-	-	8960
25	-	-	-	-	-	-	-	8052	-	-	-	-	8052
26	-	-	-	-	-	-	-	-	3621	1888	-	-	3043
…	…	…	…	…	…	…	…	…	…	…	…	…	…
50	-	-	-	-	-	-	-	-	-	-	-	-	-
All (average)	1081	945	1836	4386	3390	2671	2986	3165	3805	3432	3506	1345	

6. Test for Fonte da Mesa PM

The Fonte da Mesa PM was tested against real production data. The test was made by calculating the Energy Production, EP, by applying real wind data to the PM for different test datasets and comparing it with actual production from the WF for the same period:

$$[3] \quad EP = \sum_{i=1}^{Ni} \left(\sum_{j=1}^{Nj} F(i,j) \cdot PM(i,j) \right)$$

where:

EP is the calculated Energy Production for the tested period;

PM(i,j) is the PM cell for wind speed bin i and direction bin j;

F(i,j) is frequency, in hours, wind speed bin i and direction bin j data pair in the dataset for the tested period and

Ni and Nj are the number of wind speed and direction bins, respectively.

The overall test was made for both Regular and Normalized PM, for the 30º D bin. Results are shown in the following table.

Table 4 – Overall test of Fonte da Mesa PM

		AEP [MWh]			**Deviations.**	
Test Period (Year)	**Recov. Rate [%]**	Real	Estim. Regular	Estim. Normalized	Regular Matrix	Normalized Matrix
1997	46%	10 388	10 690	10 731	2.9%	3.3%
1998*	68%	15 247	15 704	15 739	3.0%	3.2%
1999*	76%	17 408	17 538	17 547	0.7%	0.8%
2000	64%	14 762	15 192	15 195	2.9%	2.9%
2001	28%	5 140	5 446	5 435	6.0%	5.8%
2002*	77%	17 486	17 855	17 642	2.1%	0.9%
2003	64%	11 895	12 284	12 275	3.3%	3.2%
				Average	**3.3%**	**3.2%**

* Years considered in Wind Farm Perf. Matrix

As it can be seen, deviations were surprisingly low, in average close to 3 % or . The highest deviation was 6.0 %, in the year with the lowest recovery rate, 2001.

In average, very small improvement regarding air density correction of PM is detected, and not consistent over all datasets.

All tests showed overestimations of EP. No final definitive explanation was yet found for this fact, however, this can be related to the fact that, according to the calculated PM, for calms measured at the reference site (first row of the PM in table 3, wind speed bin from 0 to 1 ms^{-1}) the WF average P is different than 0. This should mean that wind intensities measured at the reference site TC1 are significantly lower than for some turbine sites or, in other words, for some occasions, even if the reference site is in a calm, some turbines may still have some, minor, wind to keep producing power. When using the PM to estimate energy yield this will simple mean that the WF is always producing energy, which is obviously unrealistic.

There is a clear correlation between the length, or recovery rate, of the dataset used for the test and results (figure 9). As expected, the longer the dataset, the lower the deviation.

In terms of sensitivity to width of D bin, figure 10 shows the test results for different PM, Regular and Normalized, with D bin widths of 30º, 15. and 5º. Tests were made only for years 2000 and 2003. There is a clear reduction of deviations with decrease direction bin width, of the order of 1/3 to 1/5.

The length of the Database used to calculate the WF PM was also tested (figure 11). The initial 3 years Database was reduced from 36 months to 2 months. The PM was compared with the dataset from 2000. The tests showed only a clear degradation of results for the 3 months long Databases, and bellow.

Finally, sensitivity to daily and seasonal patterns was also tested. Figures 12 and 13 show test results for the Regular 30º bin PM calculated considering only Nighttime, Daytime, Winter and Summer observations from the 3 years Database. The test dataset was, once more, year 2000. In this case, goodness of results is not dependent of daily or seasonal patterns. Deviations are within the same order of magnitude and no degradation of performance can be indicated.

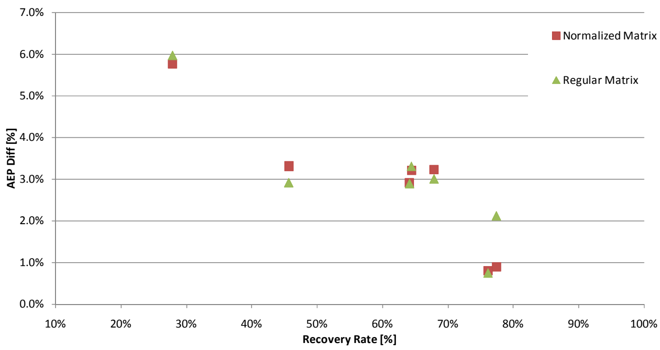

Figure 9 – Errors in EP estimates and length of the test datasets

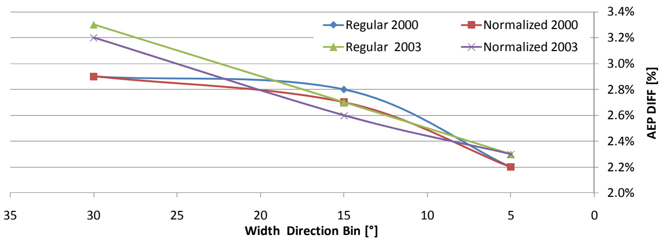

Figure 10 – Errors in EP estimates and direction bin width of the PM

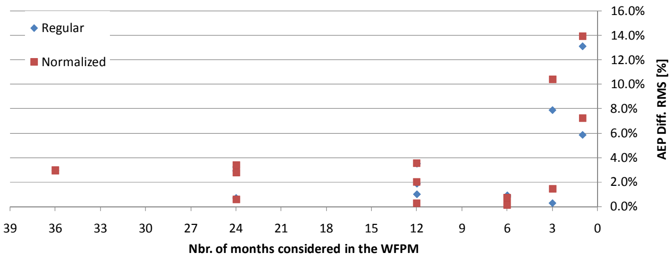

Figure 11 – Errors in EP estimates and length of the PM Database

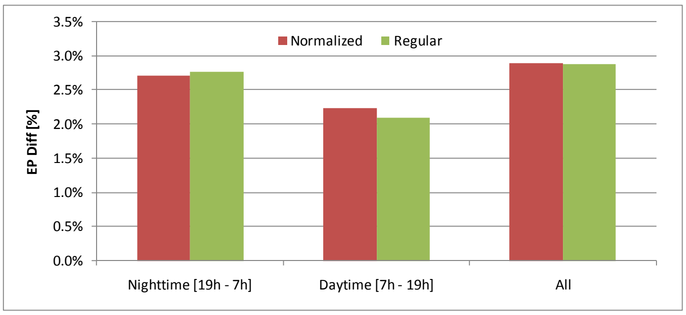

Figure 12 - Errors in EP estimates and sensitivity to daily wind patterns

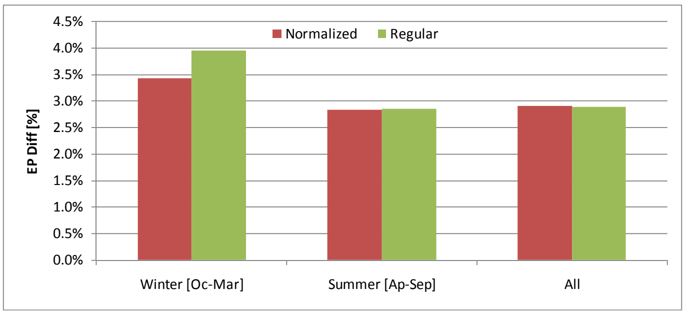

Figure 13 – Errors in EP estimates and sensitivity to seasonal wind patterns

7. Conclusions

For the studied case, the PM described very accurately the WF energy production behavior as a function of wind measurements at the reference site. For the tested datasets, an average error of around 3 % was found when comparing actual energy production with energy yield estimated with the use of the calculated PM.

The test results showed what seems to be a systematic over-prediction of energy yield.

Several simple sensitivity tests were conducted to grossly assure the consistency of results. These, again, were very satisfactory.

No relevant benefit to accuracy was found by applying the air density correction.

As expected, the PM will tend to produce better results if longer Databases are used to construct it. However, even for only 3 months long Databases, deviations were only of 6 %.

As expected, the increase in wind direction bin resolution should increase results accuracy.

No dependence on daily or seasonal patterns was found on the tests performed.

While very promising, more studies have to be done to confirm the results presented in this paper. Some of the issues to be studied are:

- Expand the test for other WFs, particularly larger WFs and not only in complex terrain;
- Investigate effect of wind behind wakes on results;
- Investigate how turbulence intensity and atmospheric stability may influence results;
- Test the influence of wind speed bin width on results;
- Implement and uncertainty analysis procedure based on Database record sampling;
- Define and test procedure to construct PMs from more than one reference sites per WF

References

[1] Paulo Pinto, Ricardo Guedes, Álvaro Rodrigues, Miguel Ferreira; “Wind Farm performance evaluation in complex terrain”; European Wind Energy Conference, Madrid 2003

[2] International Electrotechnical Commission, International Standard 61400 Part 12.1, Wind Turbines: Power Performance Measurements of Electricity Producing Wind Turbines, 2005