FIRST MEASUREMENTS ON DANmark 36 - 525 KW WIND TURBINE

Niels Vilsbøll
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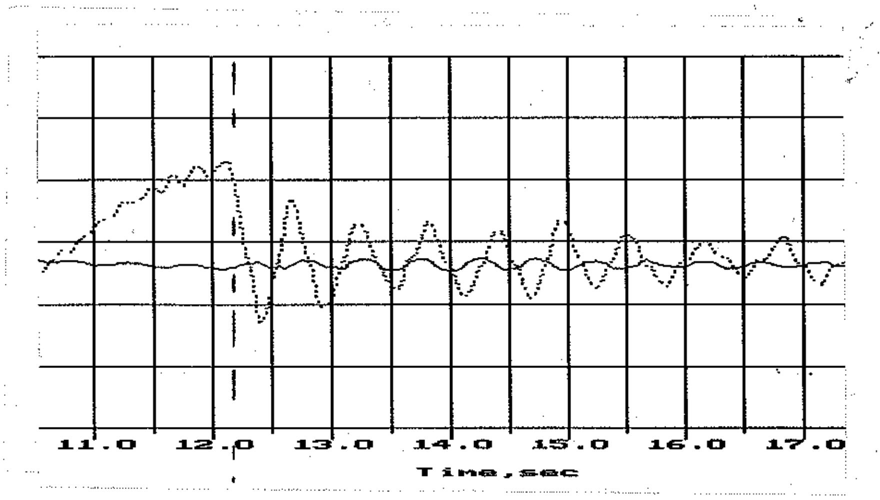
Cristian Tantareanu



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Preface

This report contains the first measurement results on the Folkecenter 525 kW wind turbine operating in Hanstholm. The measurements took place in October and November 1992, following the commisioning of the turbine. The blades pitch angle is set-up to the -2.7 degrees value. The optimum value for this angle will be set-up later.

The present report should be considered together with a previous made report, " The research measurement system on the Danmark36 wind turbine" which gives details about the wind turbine design features, the site description, the measurement schemes and technique, the instrumentation.

The softwares used are: Notebook as data aquisition software and several sofwares made by the authors in Turbopascal as analysis softwares. The RISO softwares (Rainflow, DataStat) and ORSP will be used in the next research phase for the long term run.

The tests will continue in order to confirm these first results, to study more detailed aspects of the operating regimes and to aquire statistical data necessary for loads fatigue analysis.

Contents

1.WIND TURBINE DYNAMIC RESPONSE

The power spectral density functions were calculated from the records of the torque and bending moments. The data were sampled at 25 Hz.

1.1.Tests at stopped rotor

Several methods were used for the mechanical excitation of the wind turbine structure in stopped position:

-activating one blade (put in vertical position) by random shocking;

-stopped rotor aligned in the wind. The wind pressure acts like a mechanical excitation of large spectrum;

- braking the rotor with the mechanical brake, during a low rotational speed regime.

For the last two cases the rotor was stopped in various positions (one of the blades vertical down, vertical high or horizontal position).

For all tests the Fast Fourier Transform analyses was performed for several measured data time series as bending moments on the blade, bending moments on the main and secondary shaft, bending moments on the tower, torque moments on the tower and shafts.

In the figures 1 to 11 one can see the power spectral densities found for the most representative tests. A TurboPascal graphic sofware was used to display the diagrams. The PSD value itself is uncalibrated (is given in primary units, $volts^2$ /Hz), and is used only to point out the important frequencies components.

This results give the following eigenfrequencies :

Table 1

T	-Tower bending (coupled with symmetric rotor)..........	0.65 Hz
R1	-Rotor and transmission torsional (coupled with tower)	1.78 Hz
FB1	-Blade flapwise (coupled with tower and rotor motions)	1.90 Hz
FB2	-Blade flapwise	2.10 Hz
R2	-Rotor and transmission torsional.....................	2.36 Hz
CB	-Blade chordwise (coupled with tower bending)..........	3.60 Hz

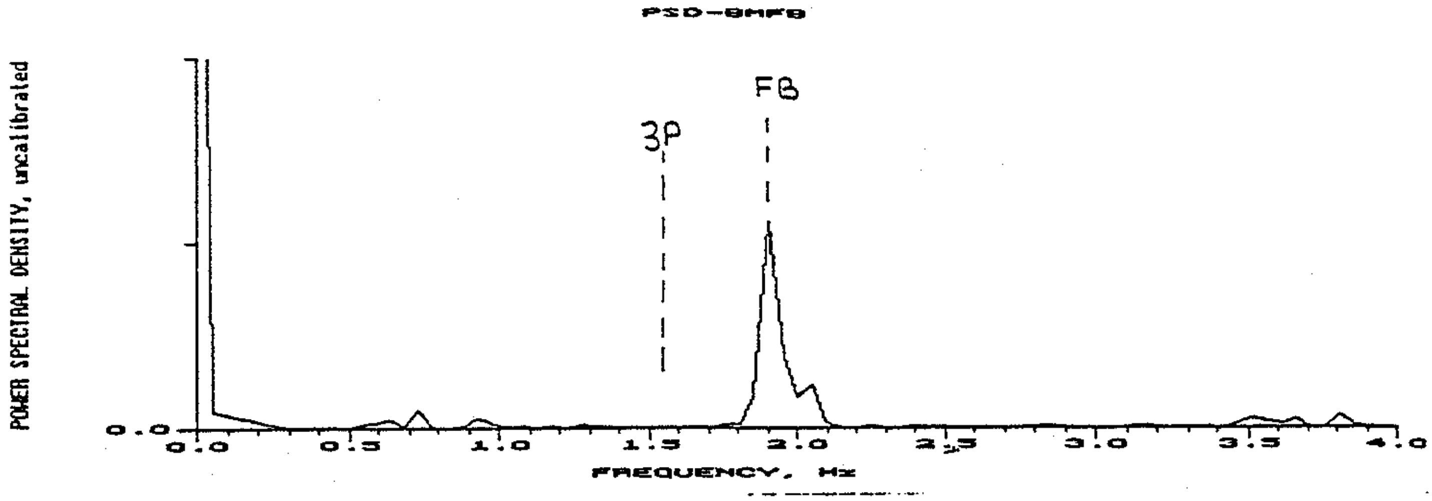

Fig.1. PSD flapwise blade bending. Rotor stopped, blade activated by shocking

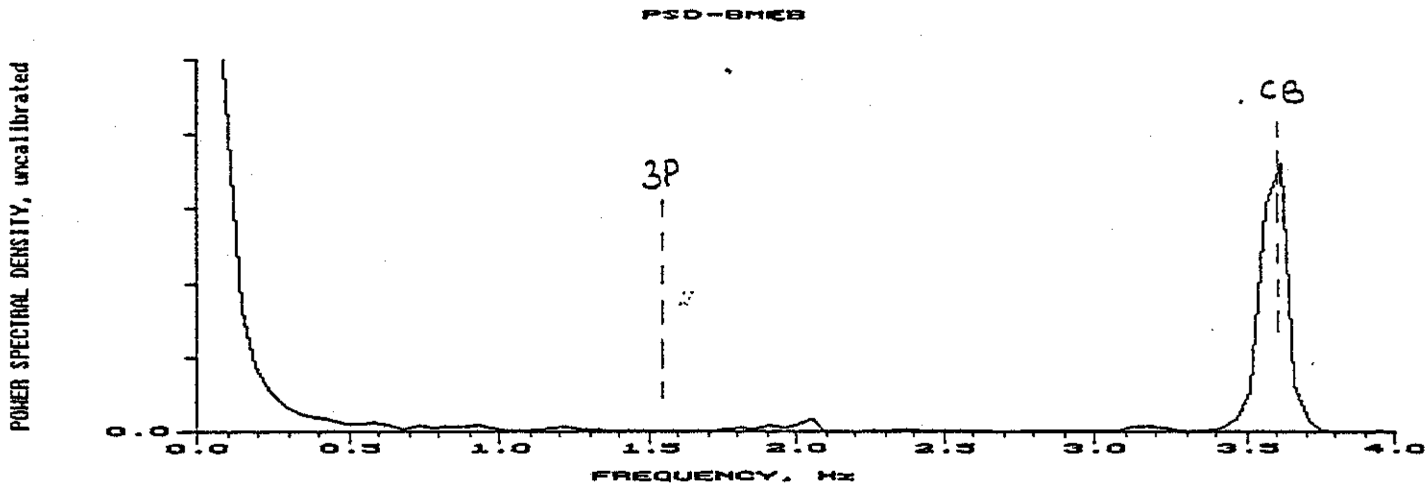

Fig.2. PSD chordwise blade bending. Rotor stopped, blade activated by shocking

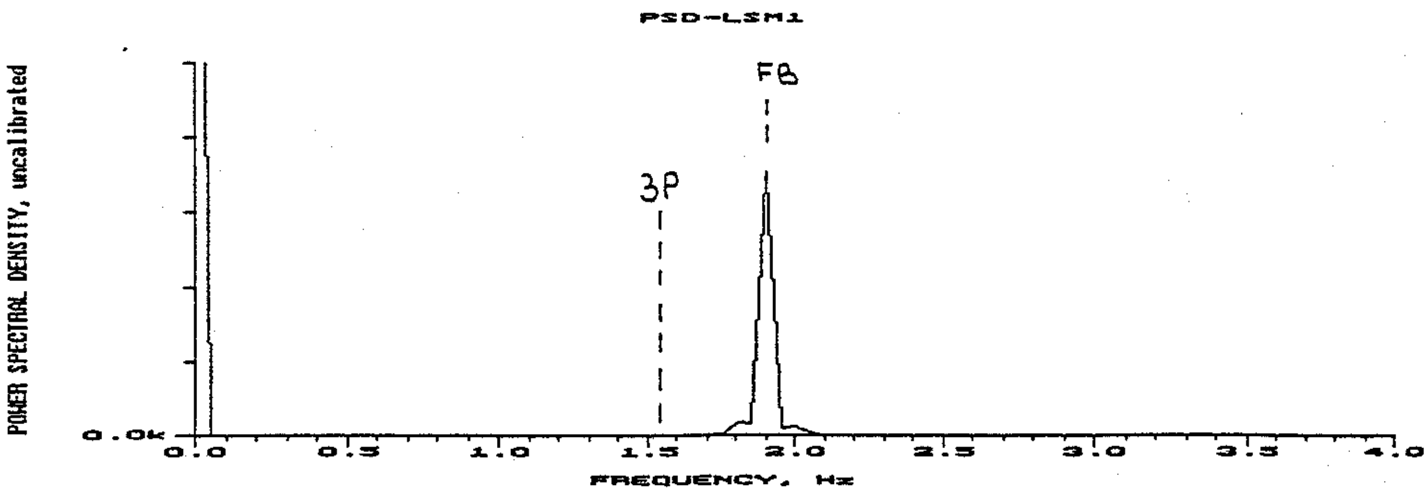

Fig.3. PSD main shaft axis X bending. Rotor stopped, blade axis X activated by shocking

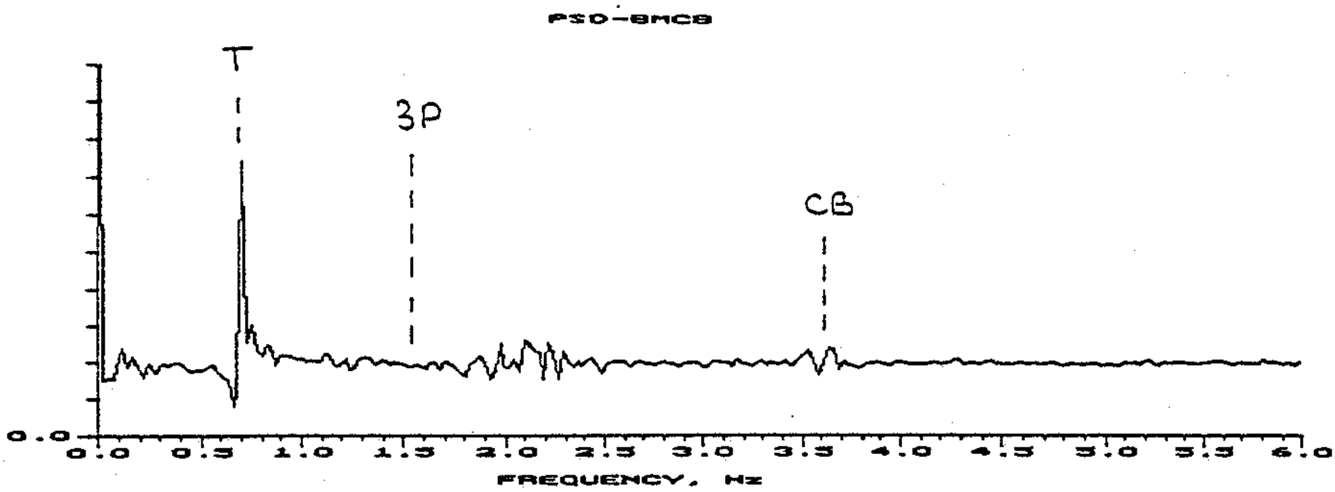

Fig.4. PSD chordwise blade bending. Rotor stopped with blade vertical up. Wind excitation.

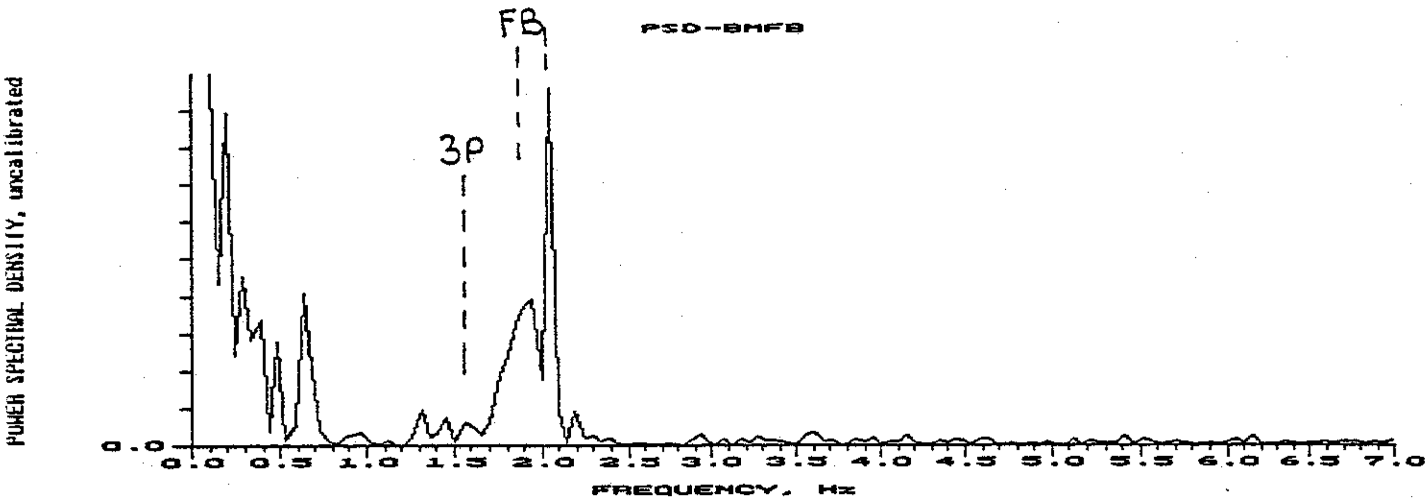

Fig.5. PSD flapwise blade bending. Rotor stopped with blade vertical down. Wind excitation.

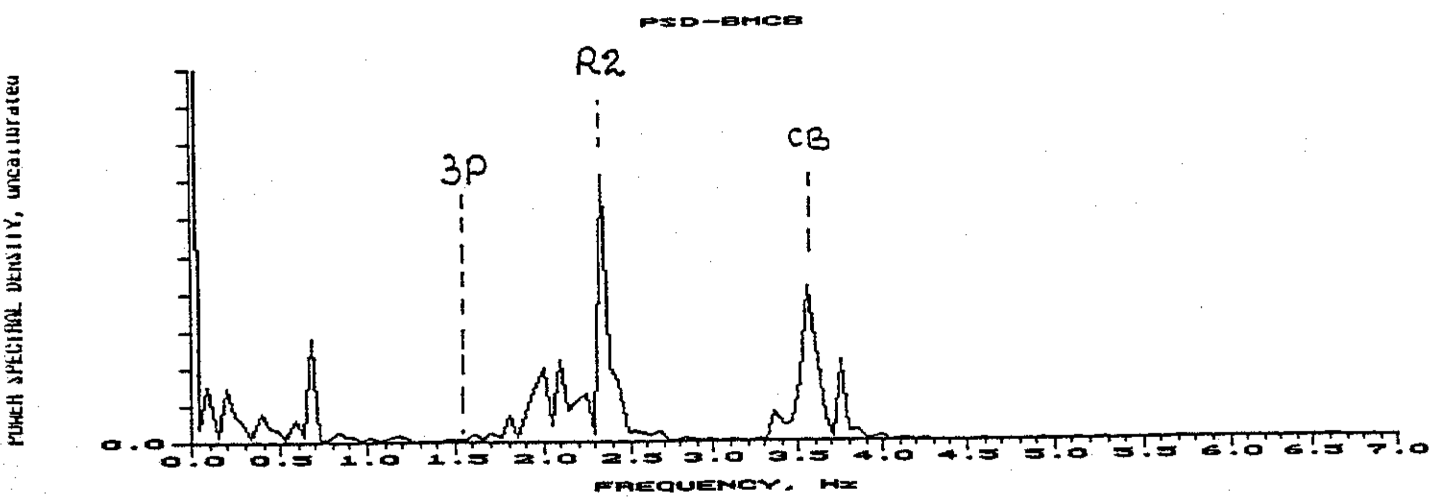

Fig.6. PSD chordwise blade bending. Rotor stopped with blade vertical down. Wind excitation.

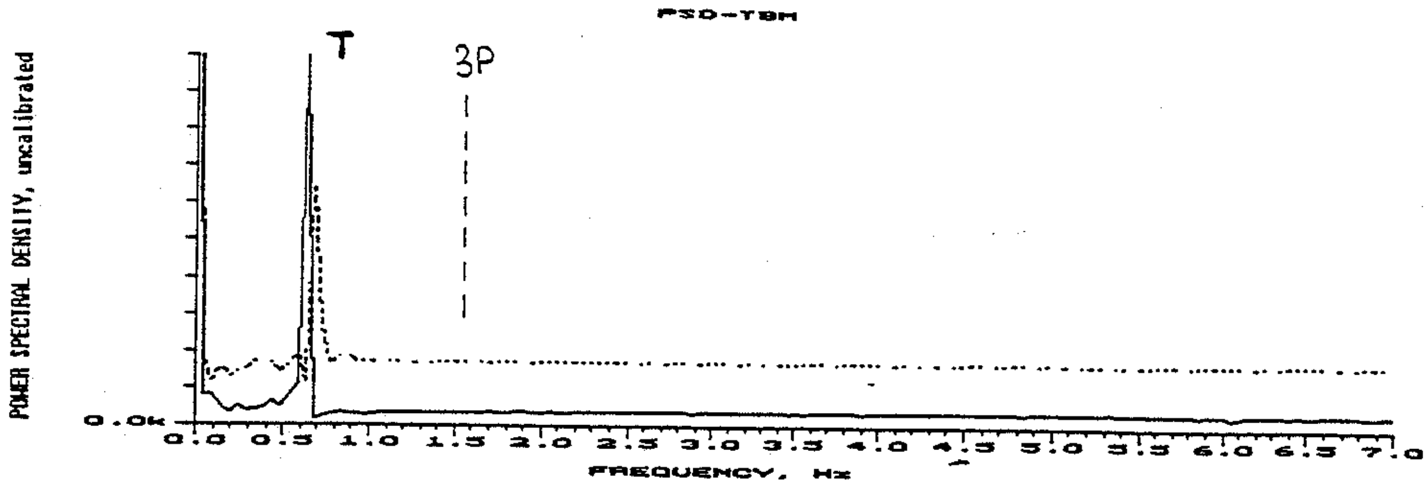

Fig.7. PSD tower 2 axes bending. Rotor stopped with a blade vertical down. Wind excitation.

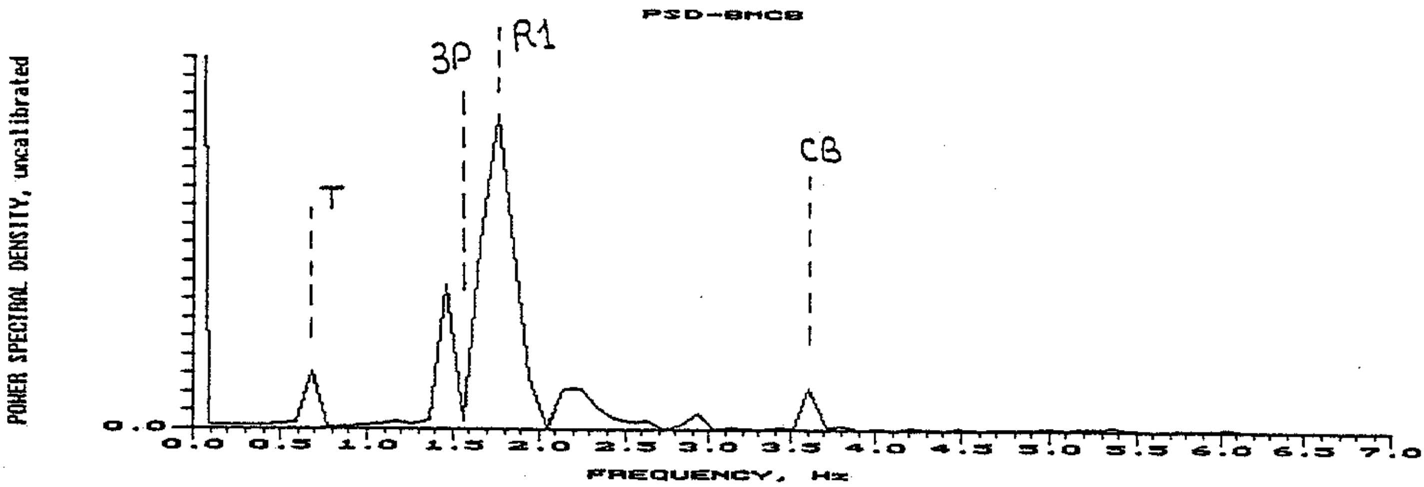

Fig.8. PSD chordwise blade bending. After a mechanical rotor brake at low rpm.

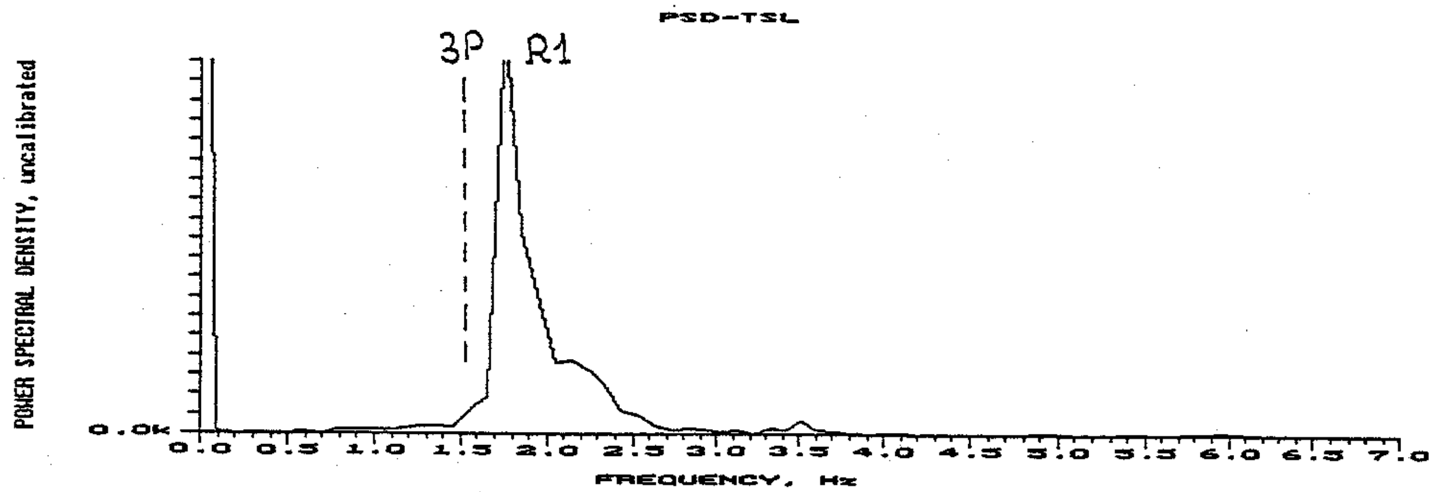

Fig.9. PSD main shaft torsion. After a mechanical rotor brake at low rpm.

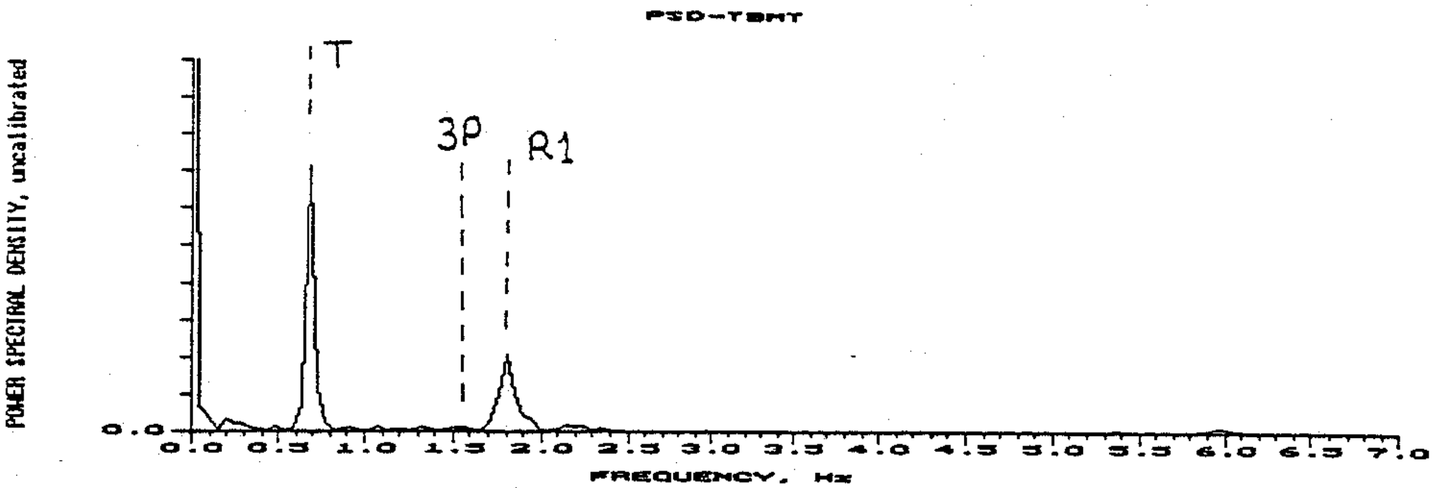

Fig.10. PSD tower torsion. After a mechanical rotor braking at low rpm.

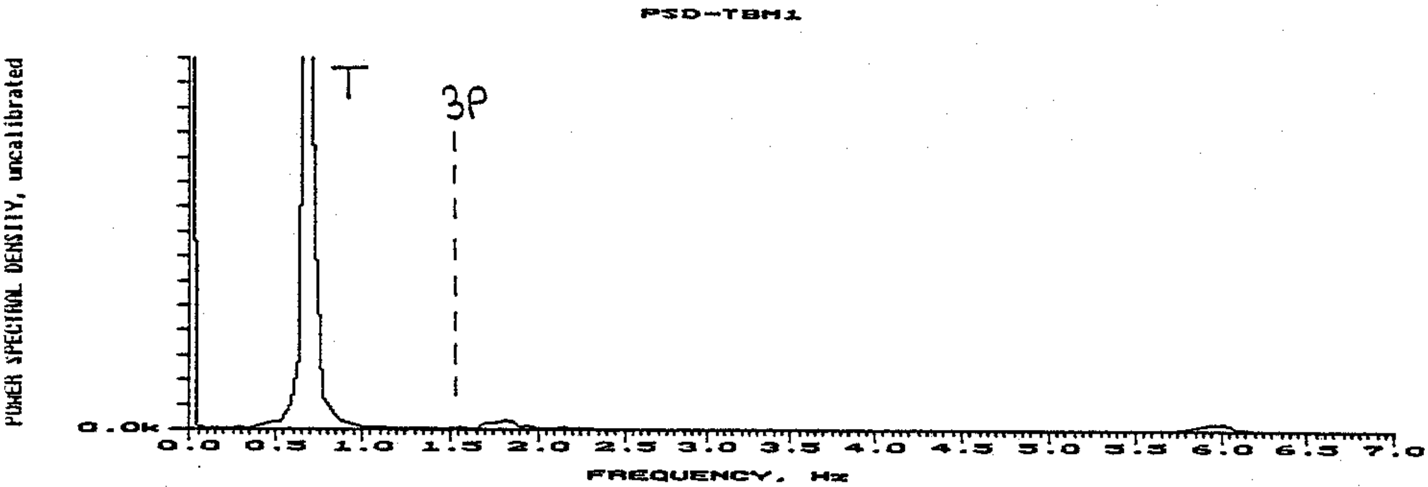

Fig.11. PSD tower torsion. After a mechanical rotor braking at low rpm.

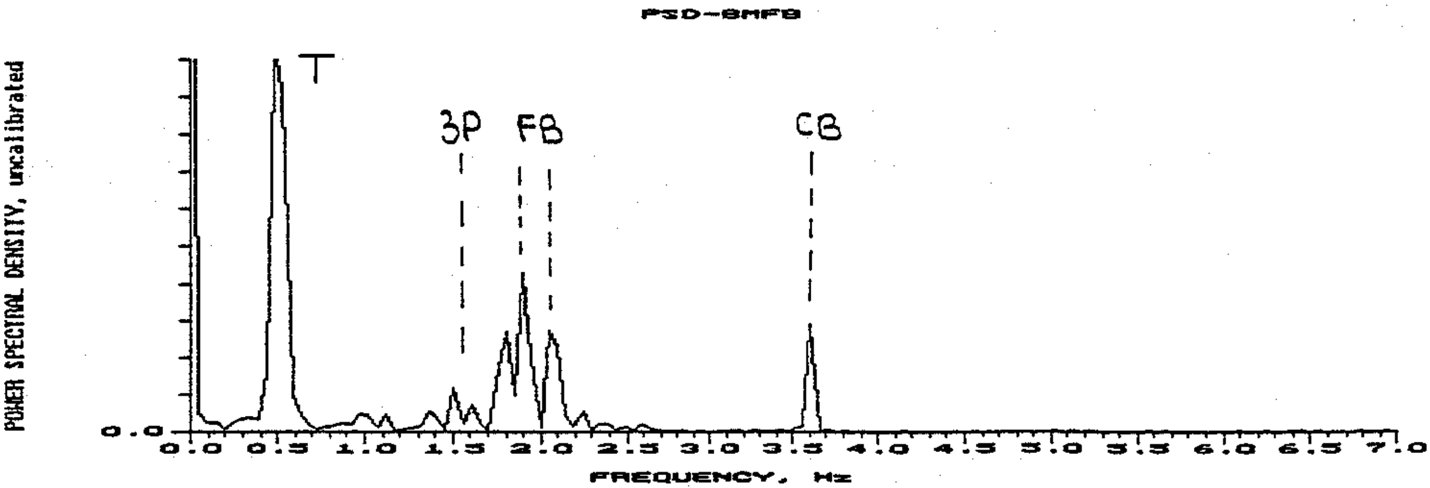

Fig.12. PSD flapdwise blade bending. Normal operation in stalling regime.

Comments

Depending of the mechanical excitation, the motions of the wind turbine structure components could be different and the coupling between these motions influences the value of the natural frequencies.

An exemple could be the coupling between the flapwise and chordwise response of the blade or the coupling of the rotor motion with the tower motion. In the first case the coupling is mainly due to the twist of the blade so that the flapwise and chordwise directions are changing with the radius of blade sections.

The most sensitive to these couplings seems to be the flapwise blade motion: here it appears a rather large frequency area (1.9..2.1 Hz) as natural frequencies. The higher limit, 2.1 Hz should be the natural flapwise blade frequency considering a rigid fixing of the root.

Beyond 4 Hz no remarkable motion was measured.

1.2.Tests at 31 rpm

The frequencies linked with the rotational speed are:

1p...0.515 Hz
2p...1.03 Hz
3p...1.55 Hz
4p...2.06 Hz

In the stages of the gearbox, corresponding to the rotor normal speed, appear also the frequencies:

2.033 Hz
7.666 Hz
25.133 Hz

The FFT analyses of the tests are shown in the figures no.12..16.

The tests were made during a stalling regime with wind speed average 17 m/s and power average 474 kW.

The chordwise blade motion is quite important during these stalling regimes. On low load regimes, the natural chordwise response is decreasing.

The most important conclusion is that no natural frequencies is close to any operational frequency (fig. 17), so that no self excited motion are likely to appear.

Further more detailed analysis of the dynamic response could regard other vibrational modes, the influence of the wind speed value or of the yaw error, the position of the yaw brake (on/off) etc.

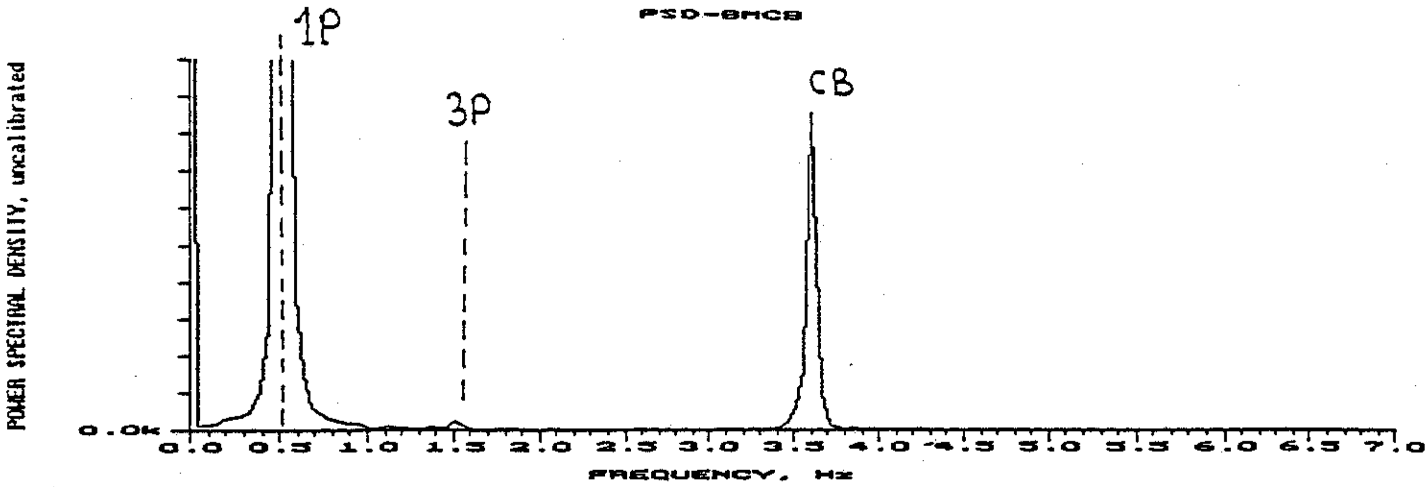

Fig.13. PSD chordwise blade bending. Normal operation in stalling regime.

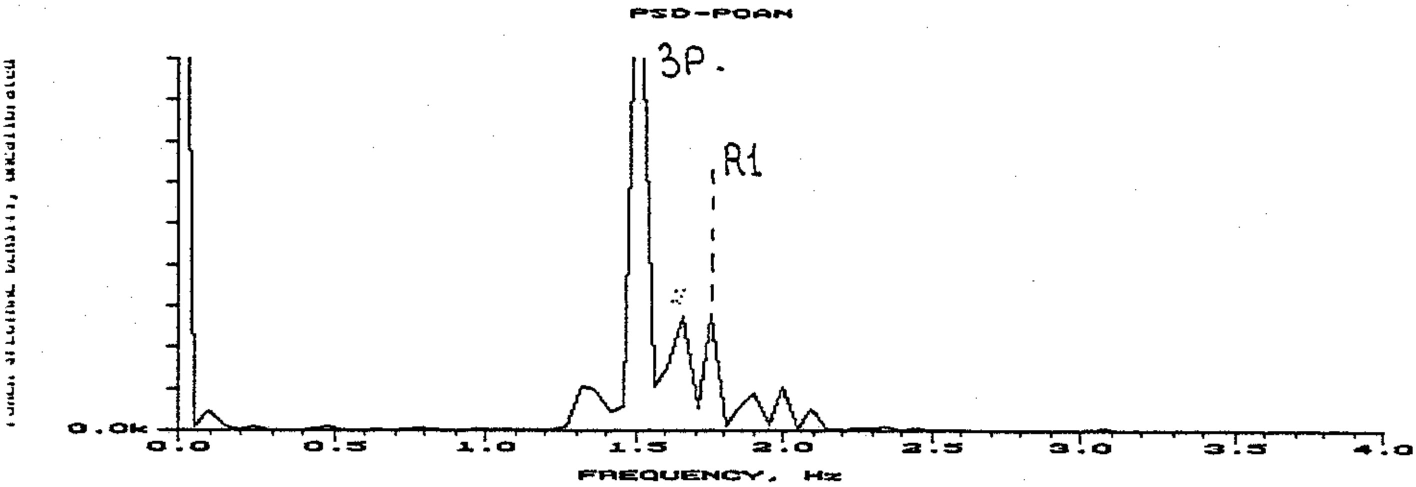

Fig.14. PSD electrical power. Normal operation in stalling regime.

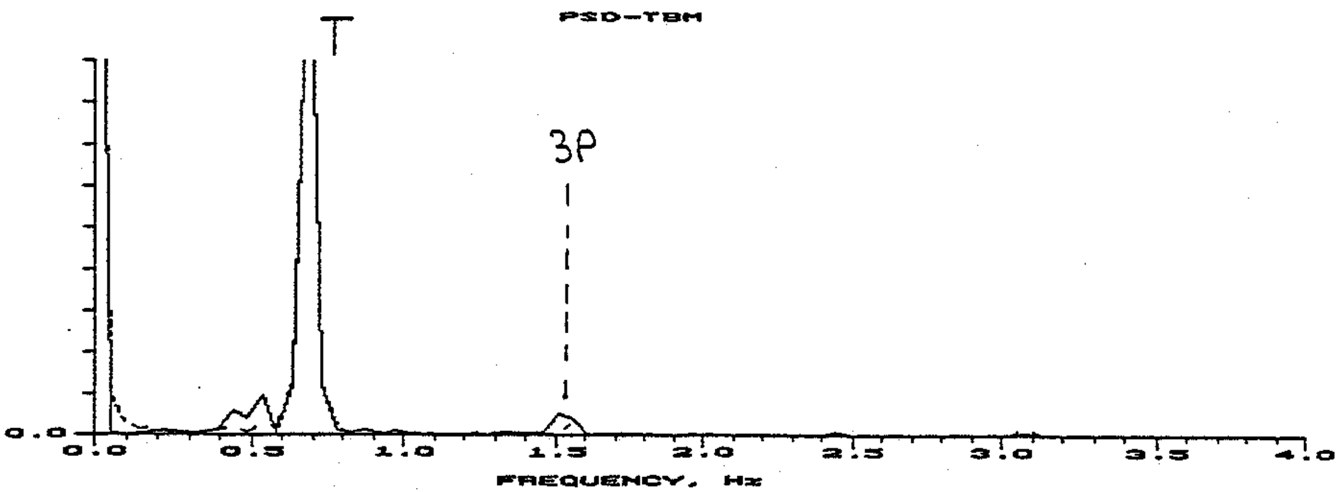

Fig.15. PSD tower bending. Normal operation in stalling regime.

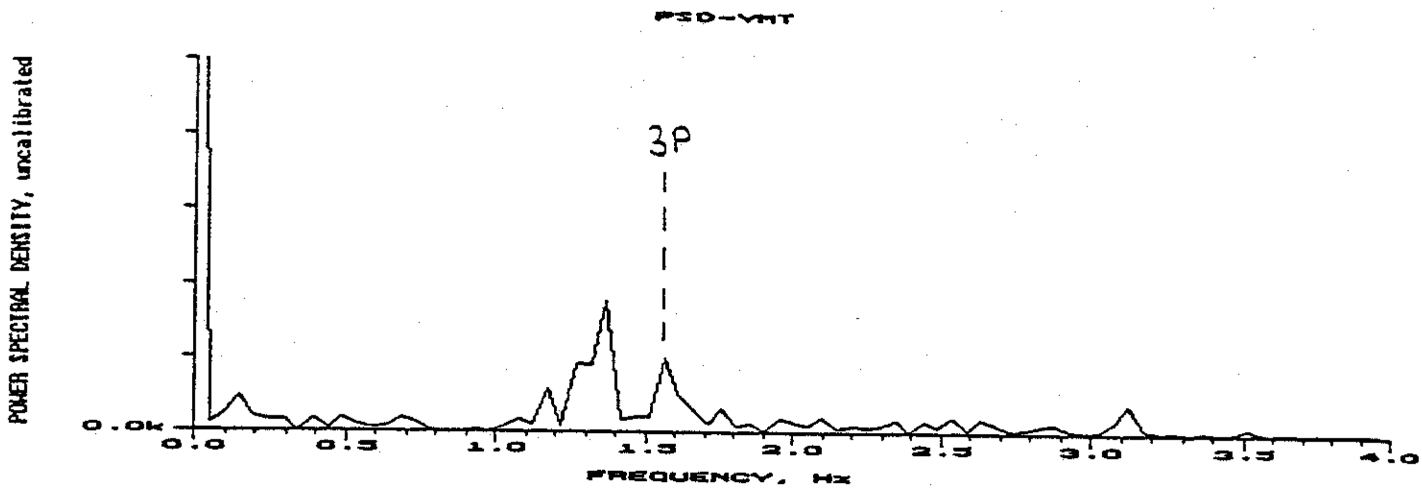

Fig.16. PSD yaw motor shaft torsion. Yawing in normal operation, stalling regime.

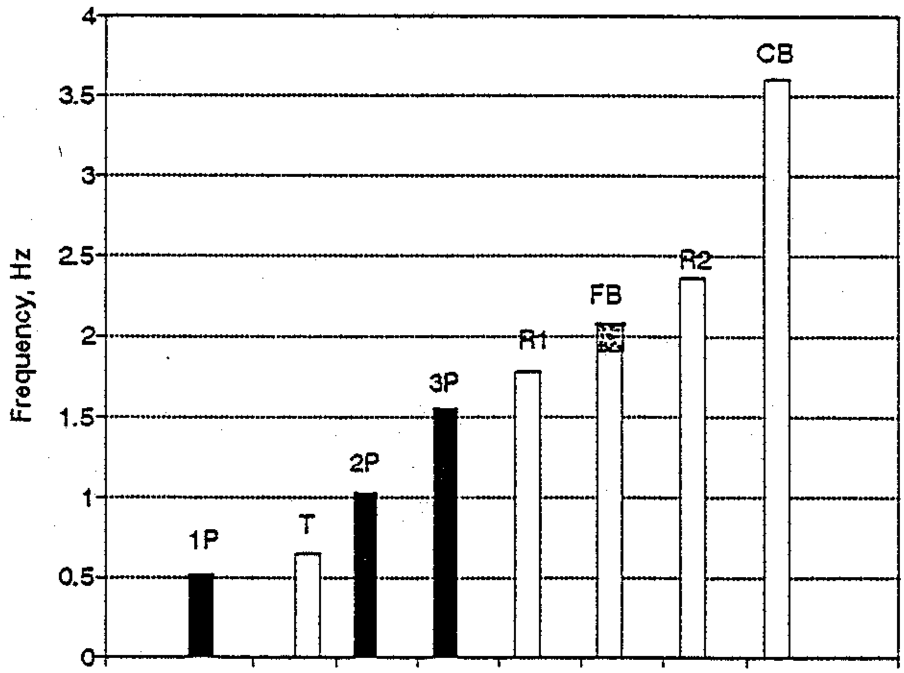

Fig.17. The identified natural frequencies as in table no.1 in comparison with the rotor rotational frequencies (1P, 2P, 3P) in operation

2.PERFORMANCE

2.1. Site characteristics

As we described in [1] the wind turbine site is characterized by an inhomogeneous topography: the sea in the Northern direction, a hill and buildings in the Southern direction. That is why a point of interest is to study the wind regime according to the wind direction.

The meteorological mast should be always upwind (fig.18, 19) so we will consider only the measurements made when the wind direction is from 180 to 360 degrees [2]. The distance between the meteo mast and the turbine is 2.1 x rotor diameter.

In order to put in evidence the turbulence of the wind in correlation with the wind direction in the fig. 20 are shown the 10 minutes averaged data turbulence-wind direction collected in November and beginning December. The turbulence is expressed as the rapport between the standard deviation and the average value.

Applying the technique of data sets bin-averaging on each 10 degrees interval we obtain the curve given in fig. 21.

The influence of the topography on the wind speed turbulence appears very clearly.

Another aspect which characterizes the wind quality is the comparison betwen the 10 minutes mean speed values at the hub height and at 10 m height.

The rapport between the two measured wind speeds data is given in the fig. 22. The processing according the bin averaging gives the dependence shown in fig. 23.

We assume as wind shear law, a logarithmic variation of horizontal wind velocity with height above ground level:

$$V(Z) = V(Z_{10}) * \frac{\ln (Z / Z_0)}{\ln (Z_{10} / Z_0)}$$

where V is the 10 minutes mean wind speed
Z is the height above the ground, 41.2 m
Z_{10} is the reference height above ground, 10 m
Z_0 is the roughness length, m

We can use the experimental data from fig.23 to solve the above equation and find the roughness.
It gives the following experimental information about the roughness in the terrain (fig. 24). This roughness values can be used in computations to find the energy production of this wind turbine or of other wind turbines mounted in the same area.

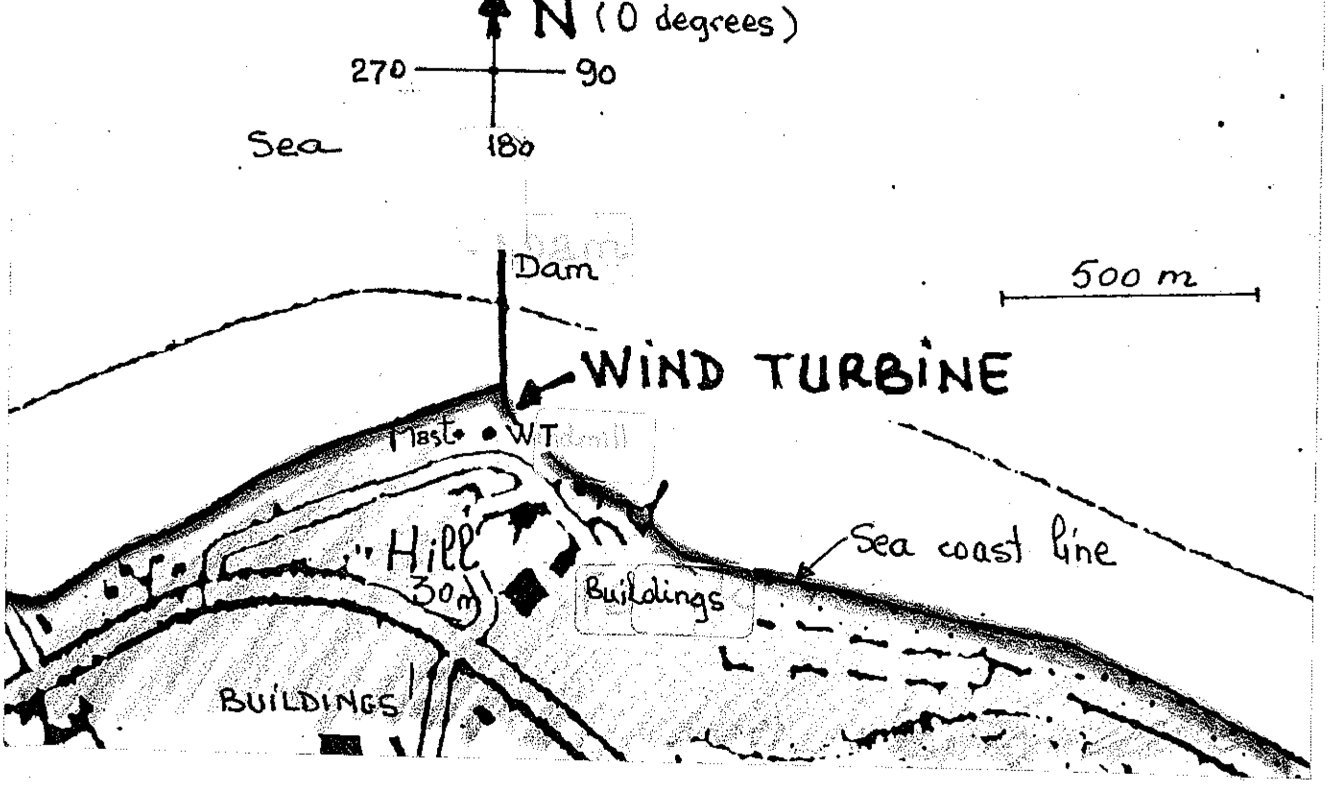

Fig. 18. The site of the wind turbine on the North Sea coast. The meteo mast is mounted 75 m to the West

Sector width (degrees)	Allowable distance (D = rotor diameter)
30 (± 15)	(1.8 to 4.0) * D
60 (± 30)	(1.8 to 3.3) * D
90 (± 45)	(1.8 to 2.8) * D
180 (± 90)	(1.8 to 2.2) * D

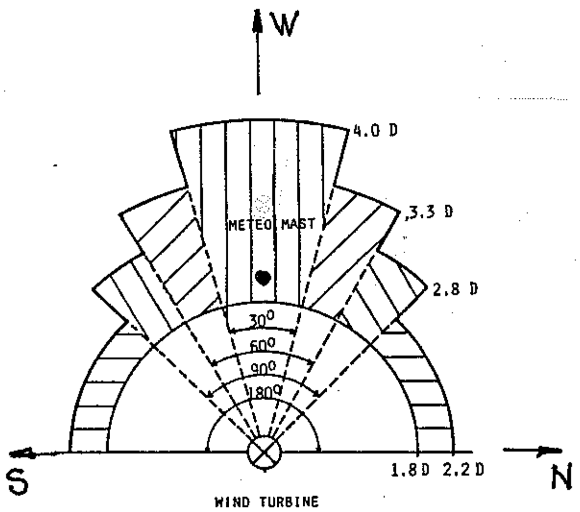

Fig. 19. The area around the wind turbine where wind speed measurements can be made [1]

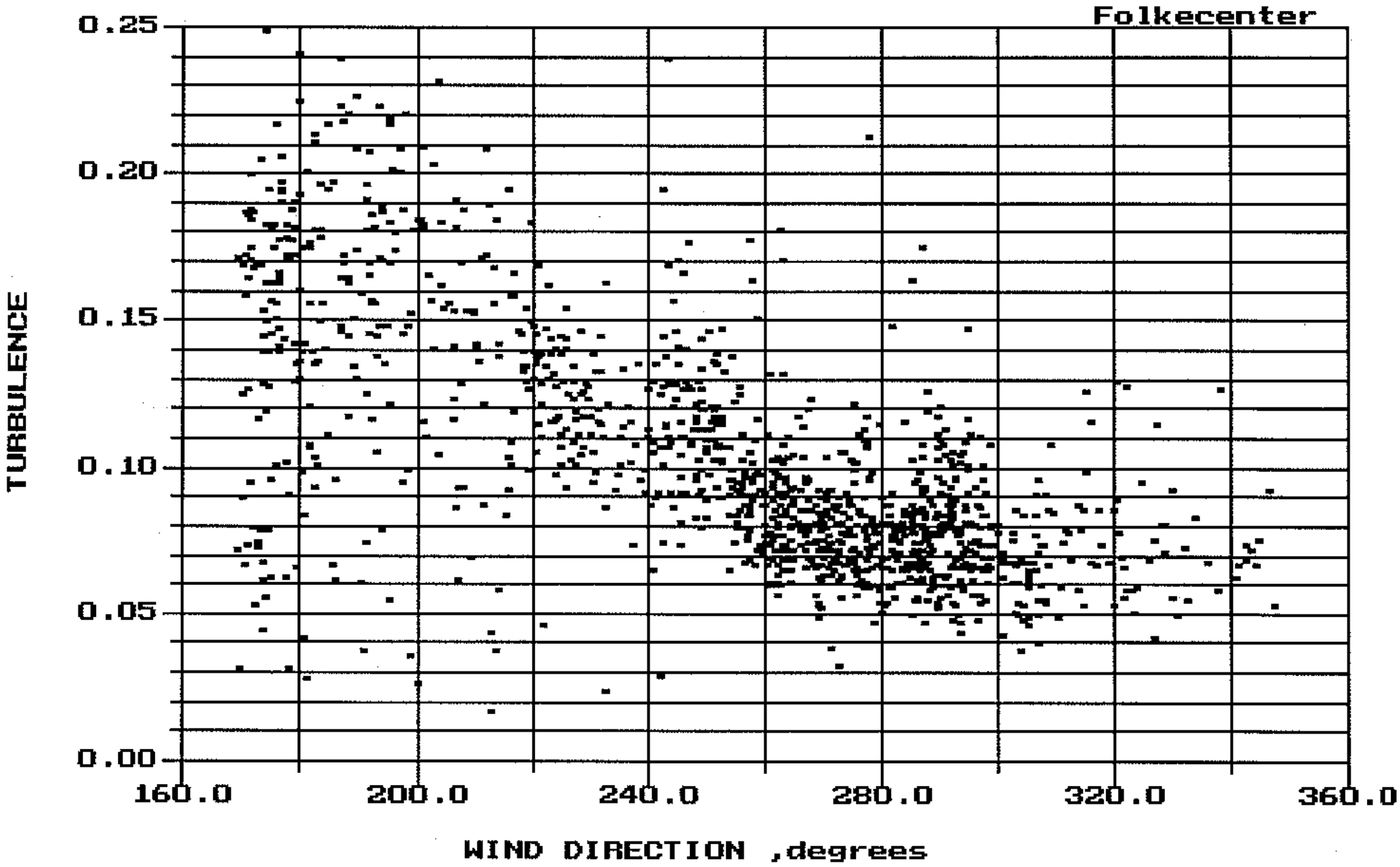

Fig.20. The wind speed turbulence (calculated for 10 minutes averaged data) versus the wind direction. All data.

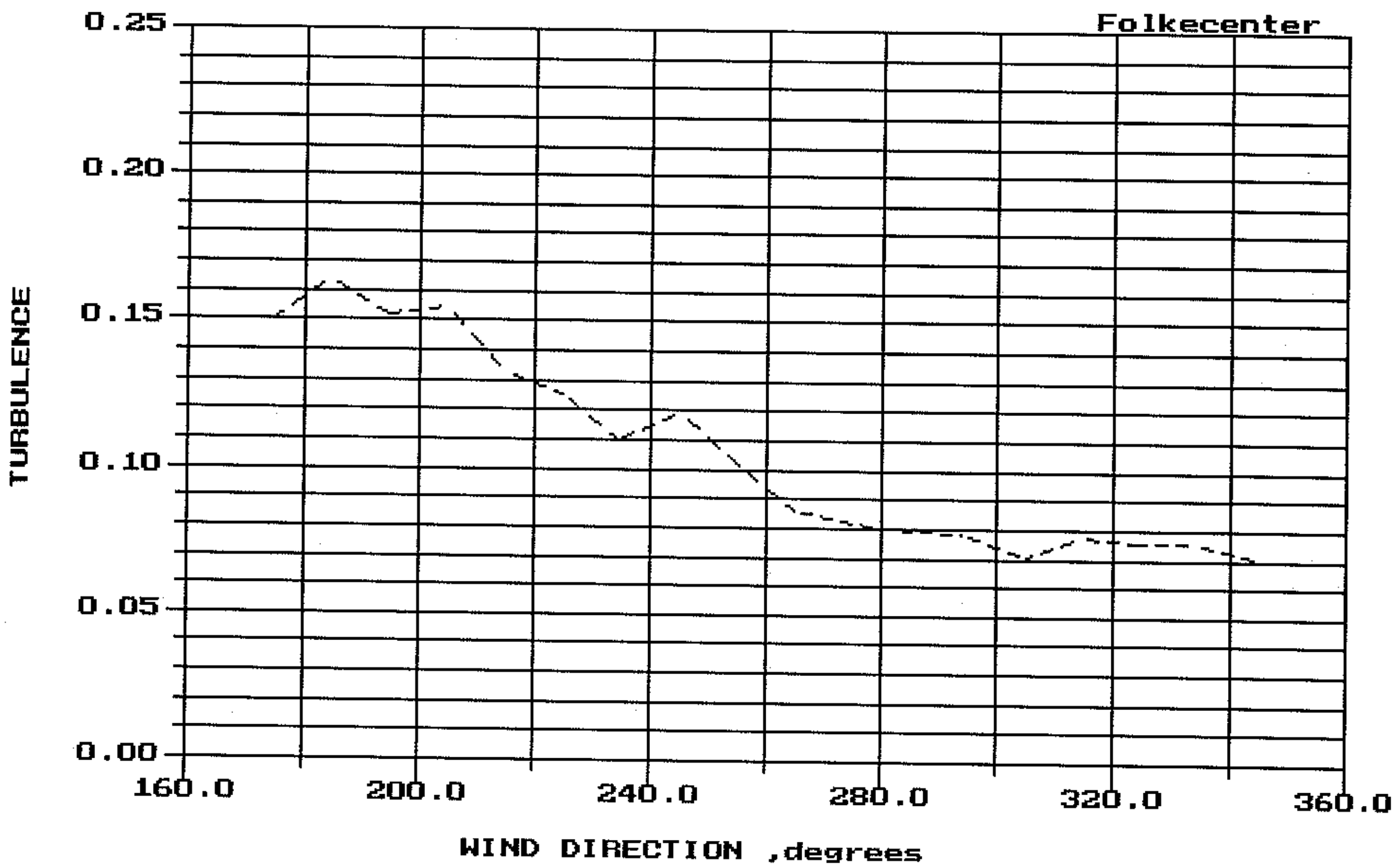

Fig.21. The wind speed turbulence versus the wind direction.

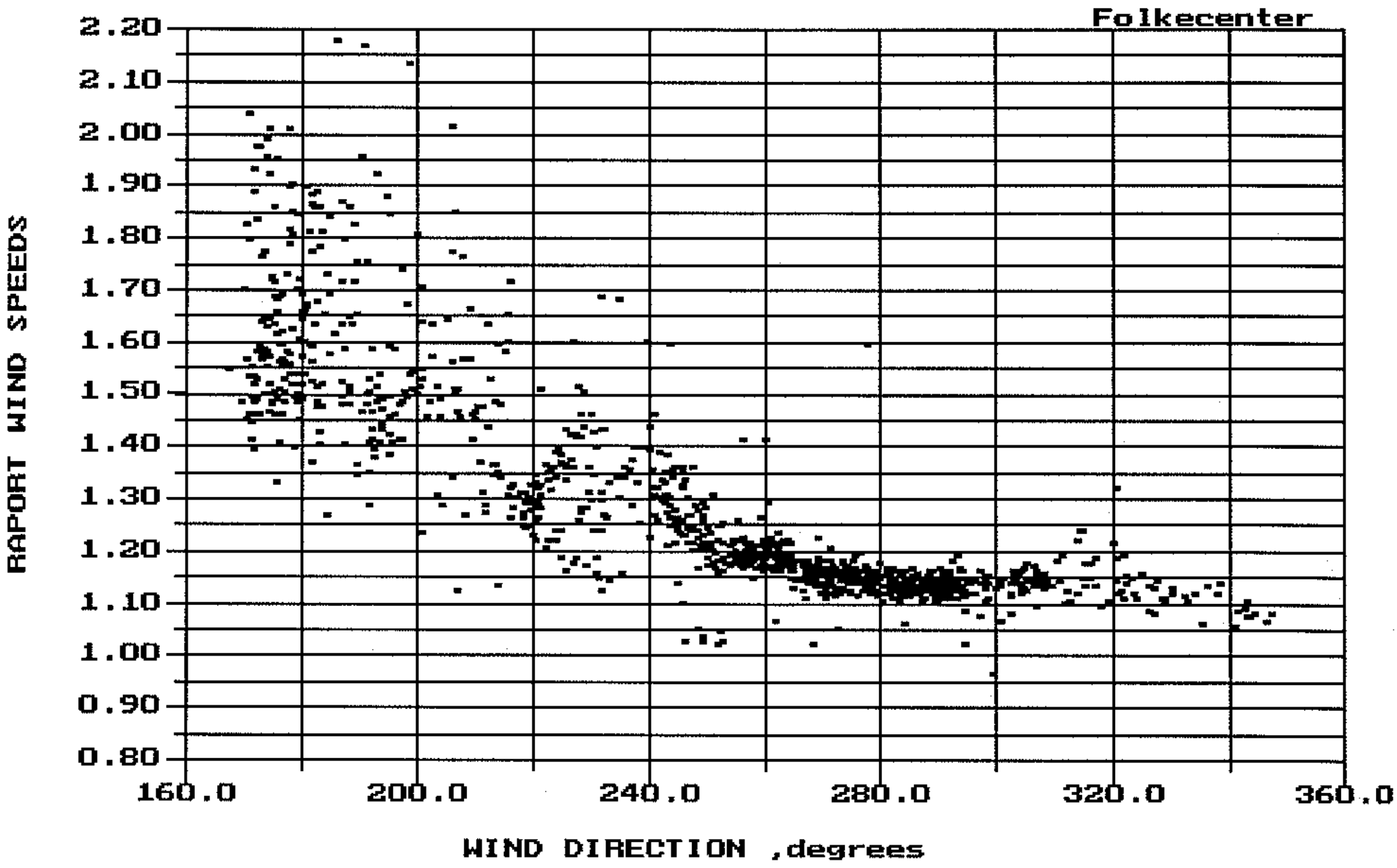

Fig.22. The rapport between the hub height wind speed and the 10 m height wind speed (calculated for 10 minutes averaged data) versus the wind direction. All data.

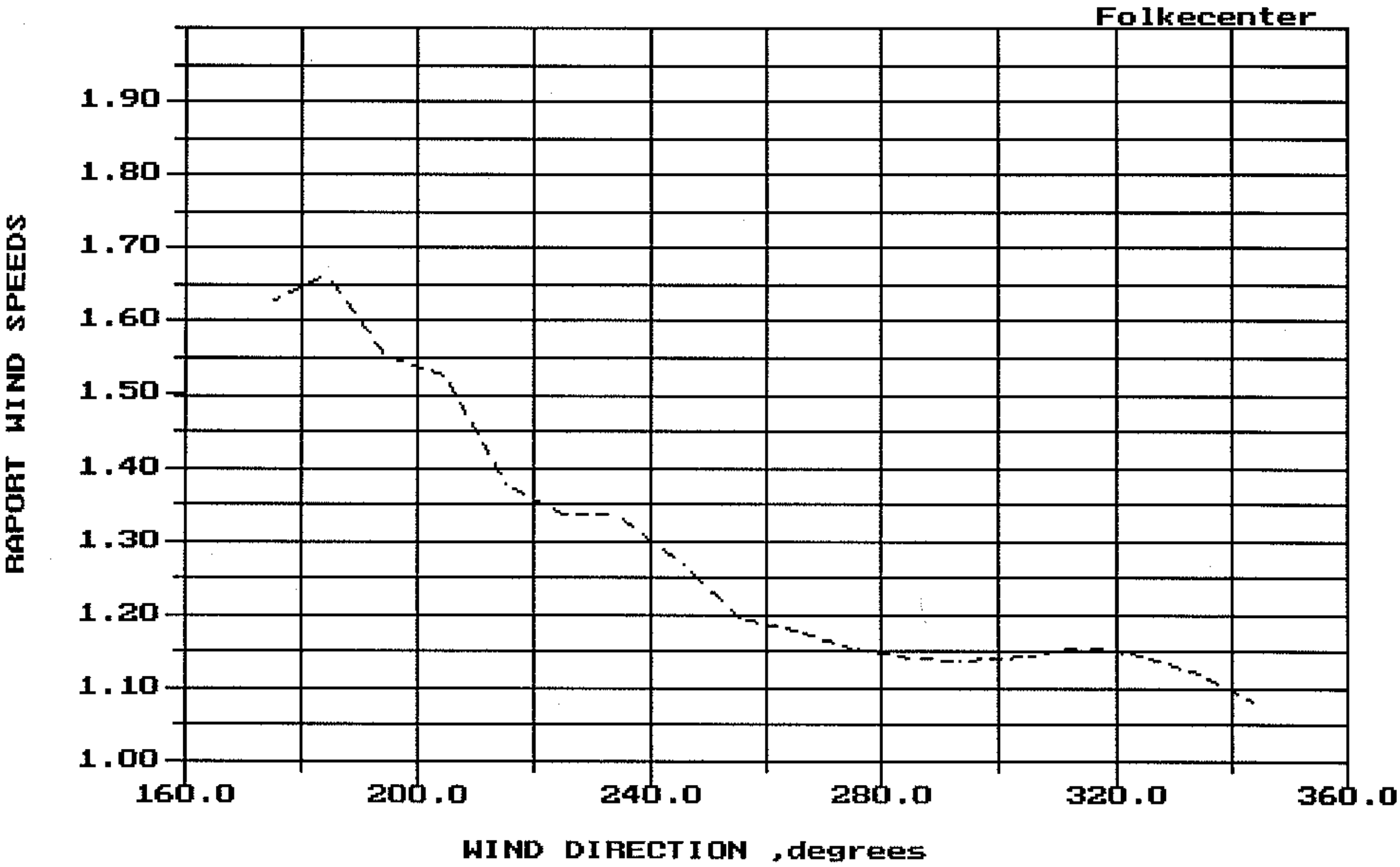

Fig.23. The rapport between the hub height wind speed and the 10 m height wind speed versus the wind direction.

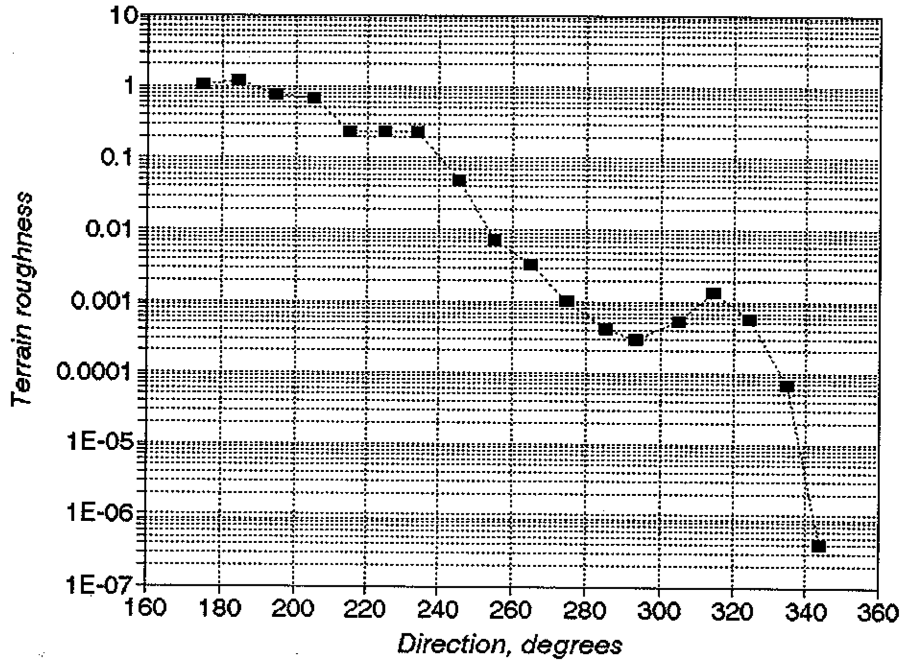

Fig. 24. The experimental identified roughness of the site terrain

2.2.Power curve

According to [2] we considered only the data with wind direction between 180 and 360 degrees. The wind speed and the power were sampled at 25 Hz and after that, following the known bins technique, averaged on 10 minutes. The bin width was chosen 0.5 m/s. The data were sorted according to the wind turbulence values:

It is important to mention again that for the first phase of the measurements the blades pitch angle was set-up to -2.7 degrees, a value which, for security reasons in the beginning, assures a power limitation in long term average around 480 kW. A further optimization of this angle will be done later.

The graphs showing all data and the bin-averaged data are given in the figures 25...34. The total number of data sets used to build the graphs is 1218. In table nr.2 one gives the results of data analysis for the turbulence 5%...10%, the most usual field of values.

The air temperature during the measurements was 2...11 C and the atmospheric pressure 985...1010 bars. The consequent correction factor applied to the wind speed-power data was between 0.98 and 1.0.

One notices that a higher turbulence (linked with the wind direction as shown in fig. 21) implies more scatter in the data and a decrease in performance.

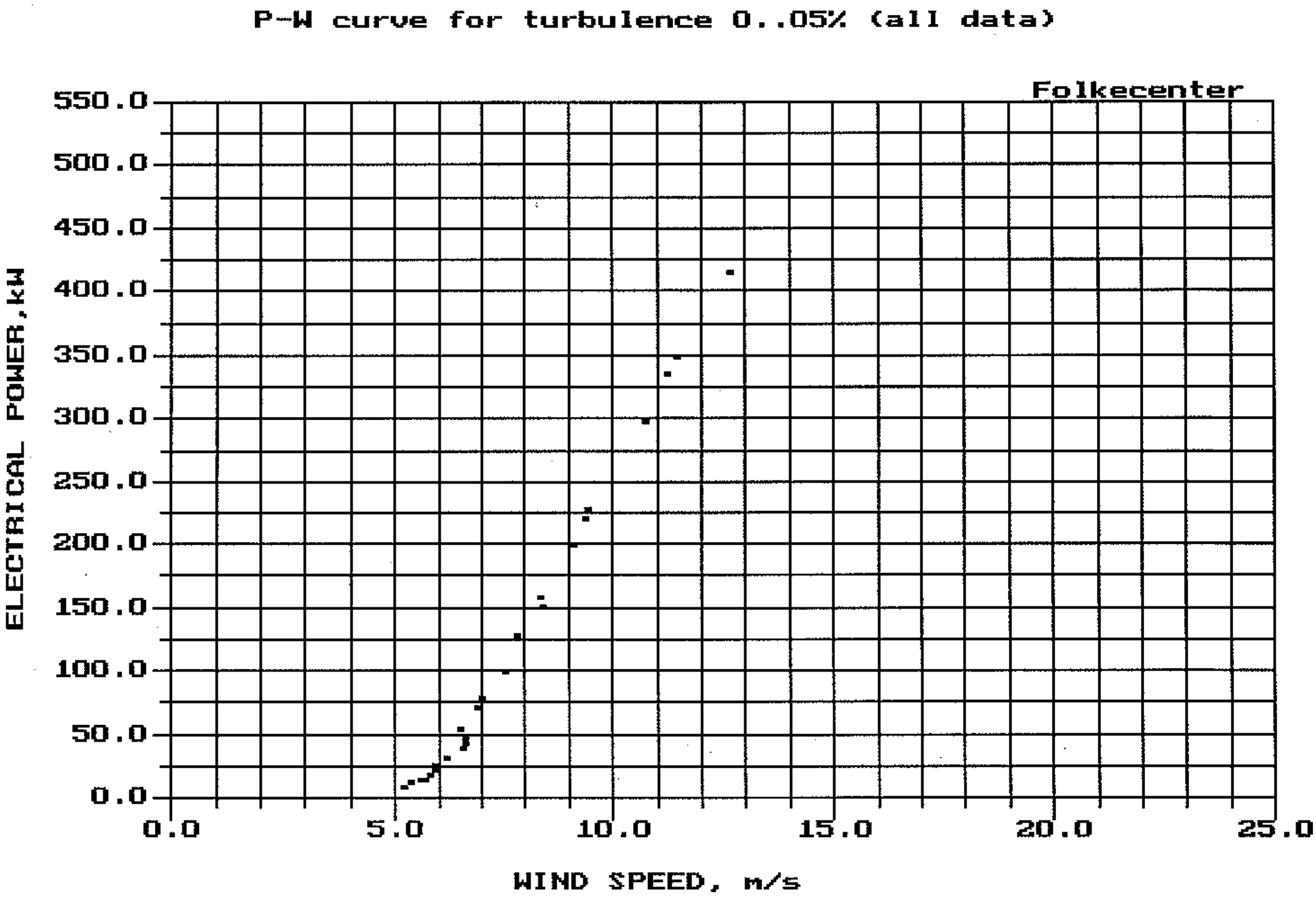

Fig.25. The power-wind speed 10 minutes averaged data. Wind speed turbulence less than 5%.

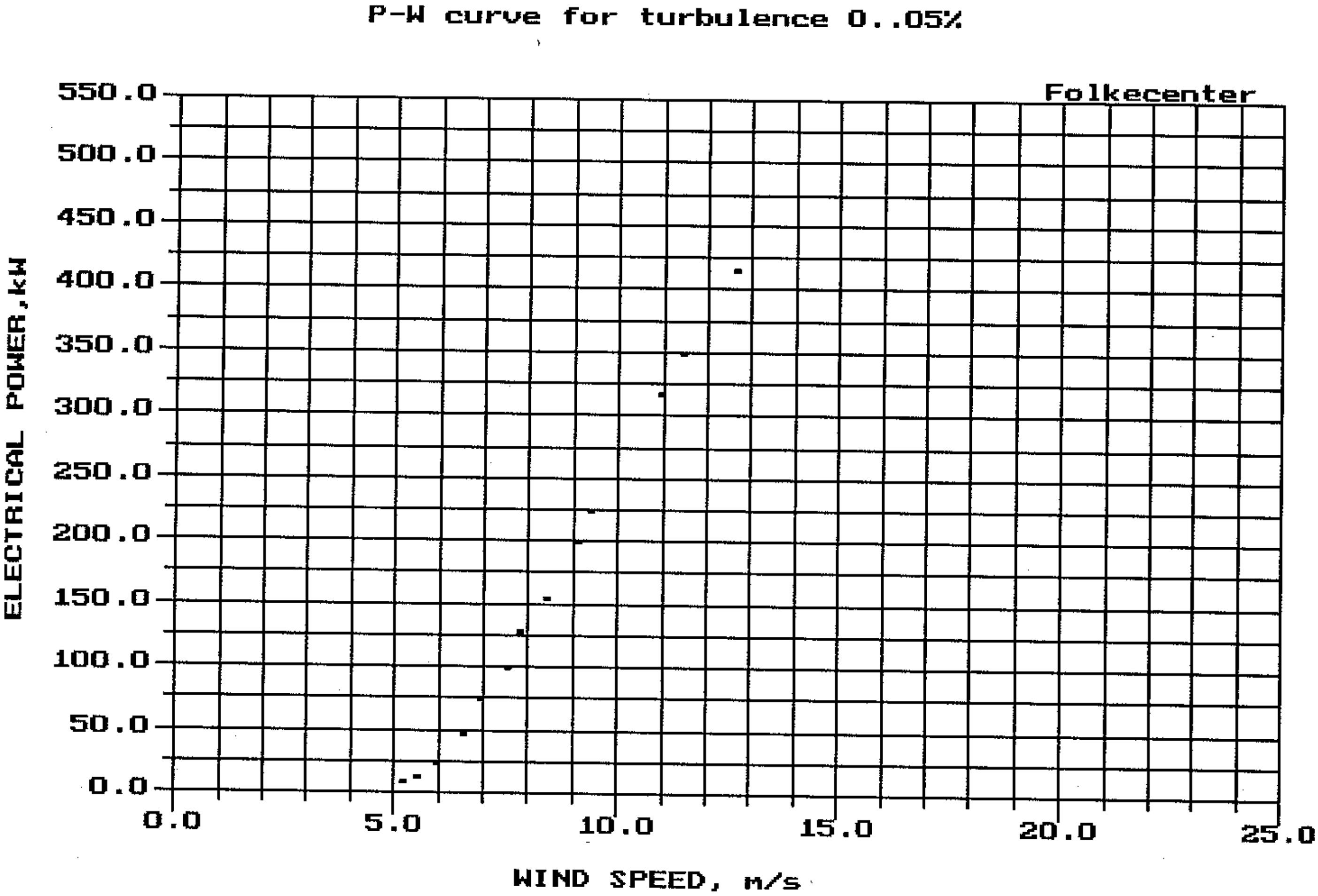

Fig.26. The bin-averaged power curve. Wind speed turbulence less than 5%.

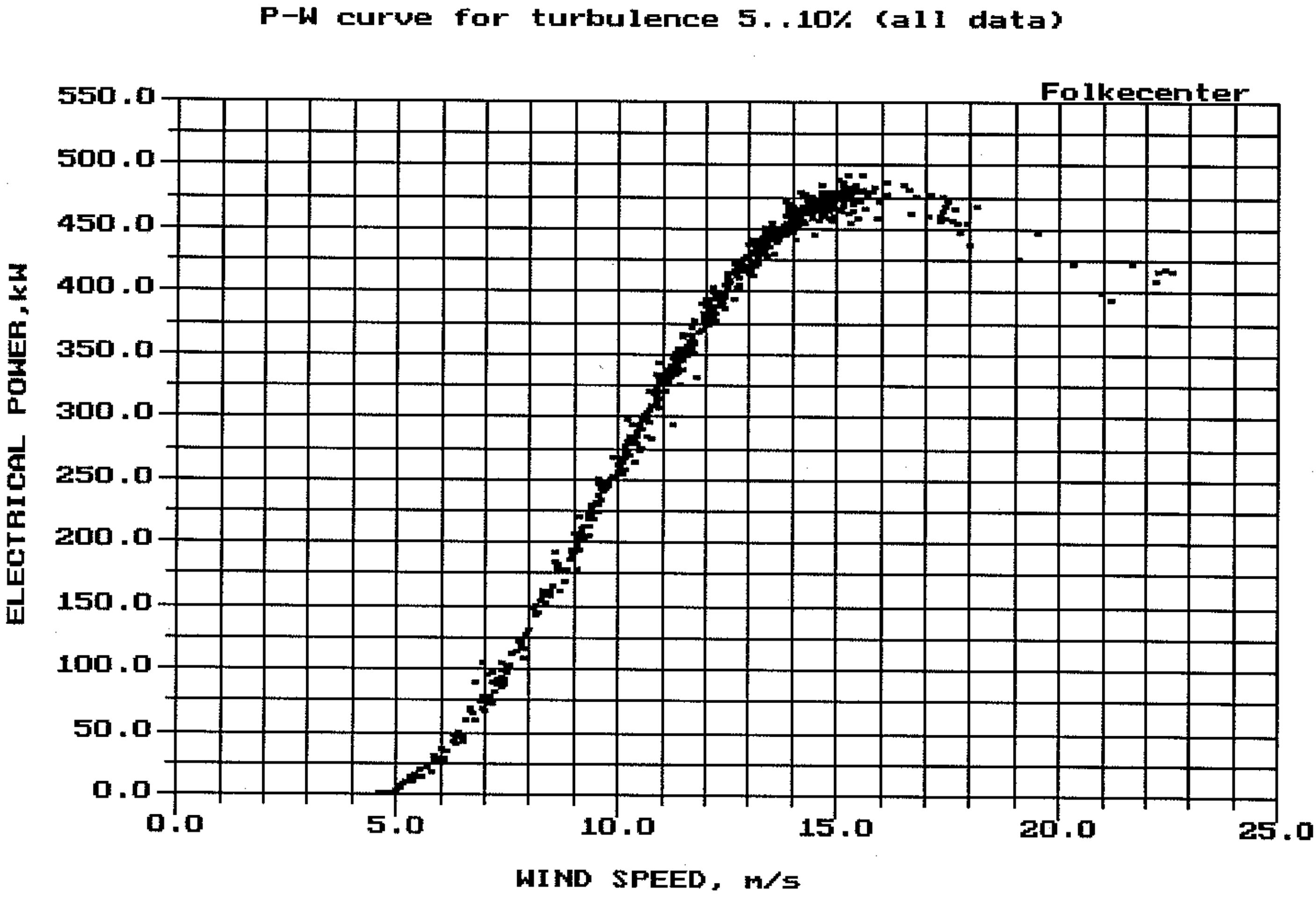

Fig.27. The power-wind speed 10 minutes averaged data.
Wind speed turbulence 5%...10%.

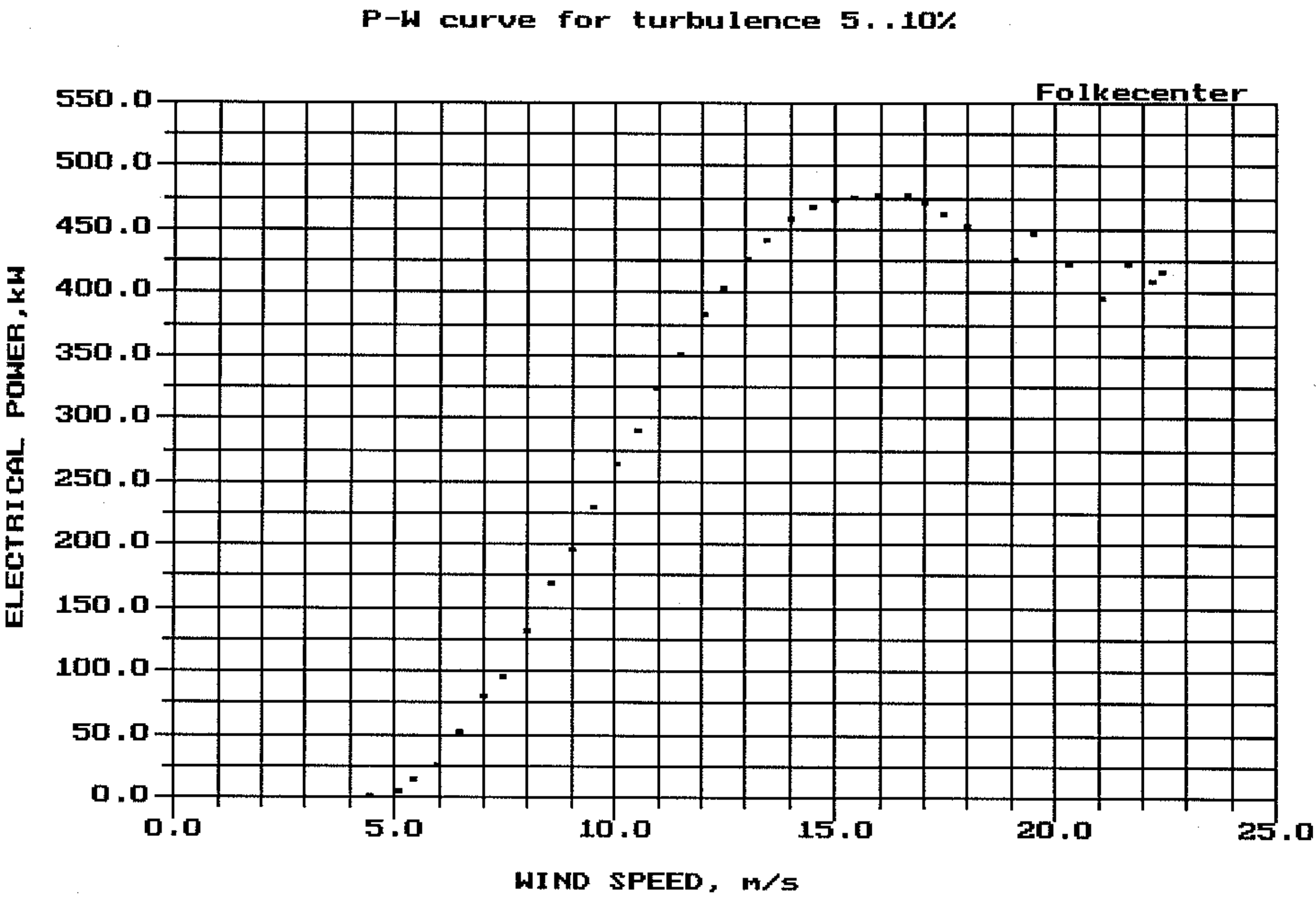

Fig.28. The bin-averaged power curve. Wind speed turbulence 5%...10%.

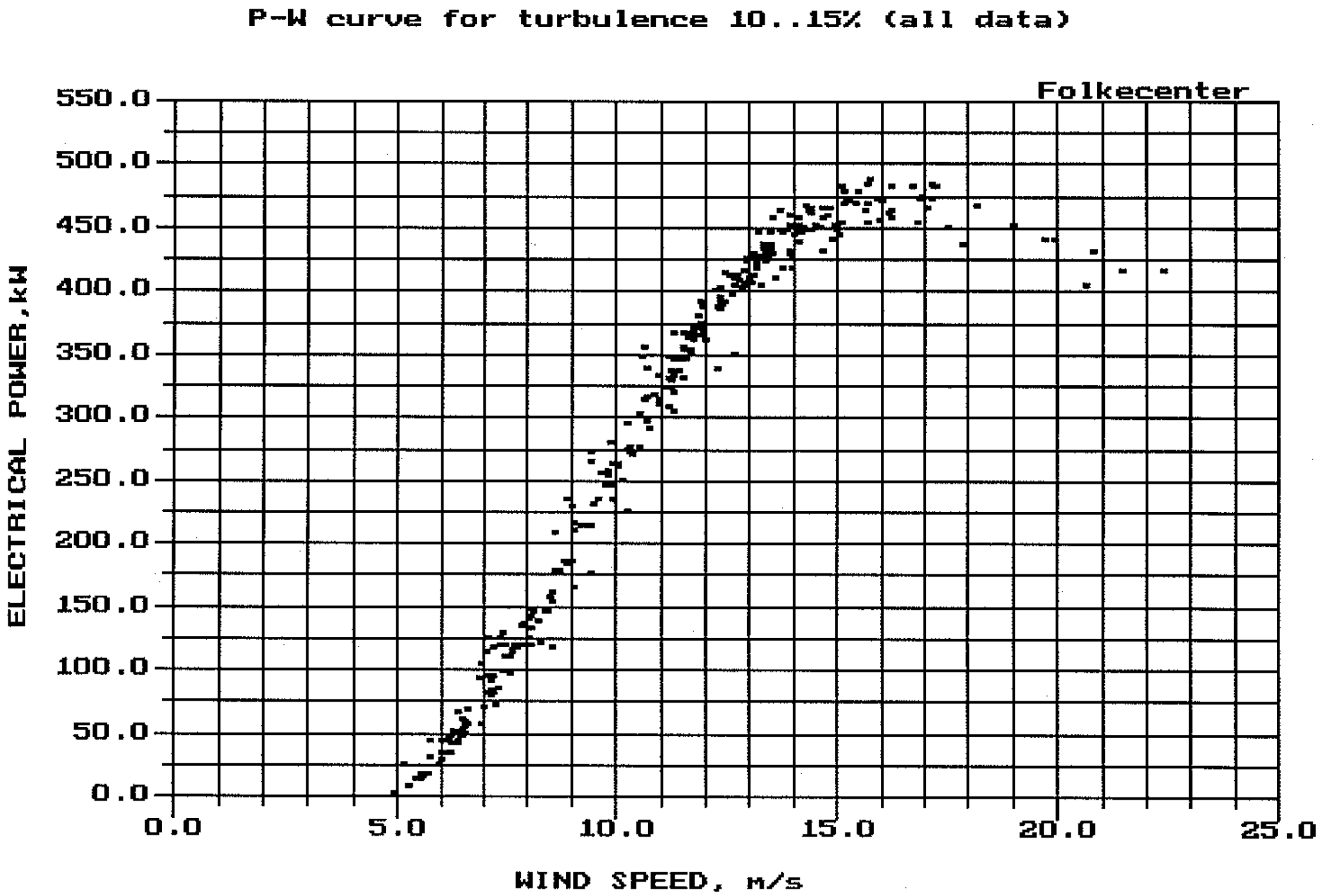

Fig.29. The power-wind speed 10 minutes averaged data. Wind speed turbulence 10%...15%.

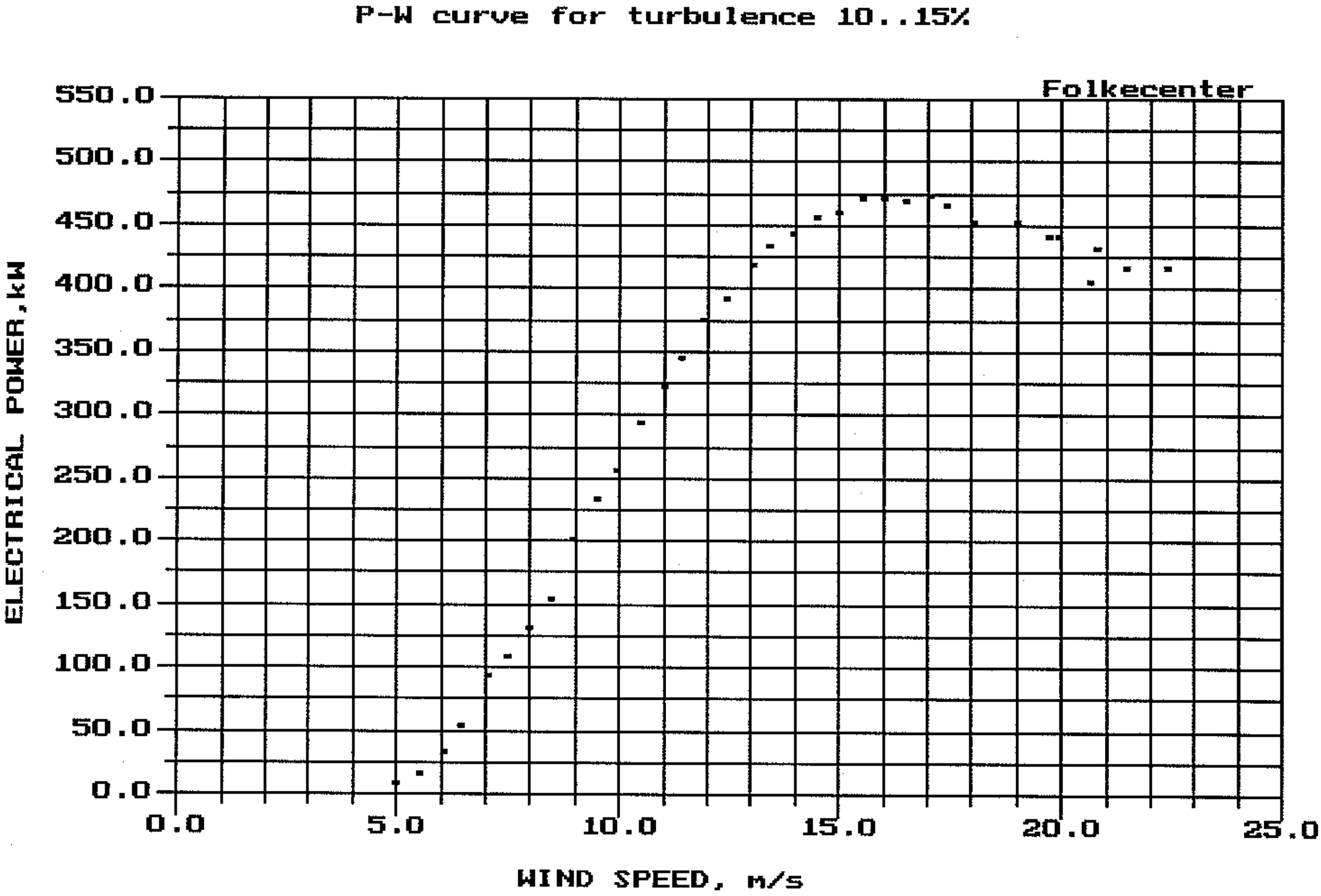

Fig.30. The bin-averaged power curve. Wind speed turbulence 10%...15%.

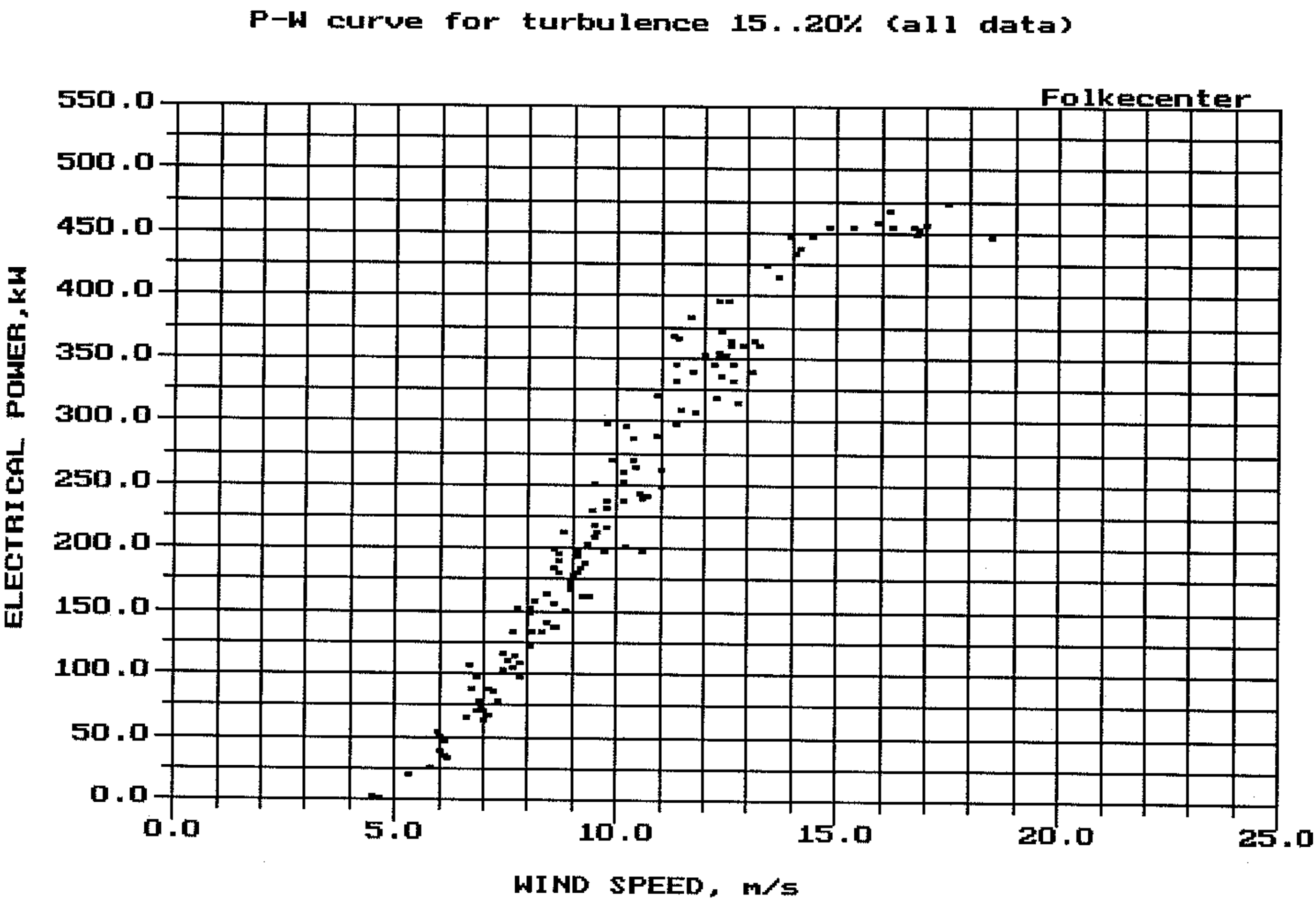

Fig.31. The power-wind speed 10 minutes averaged data. Wind speed turbulence 15%...20%.

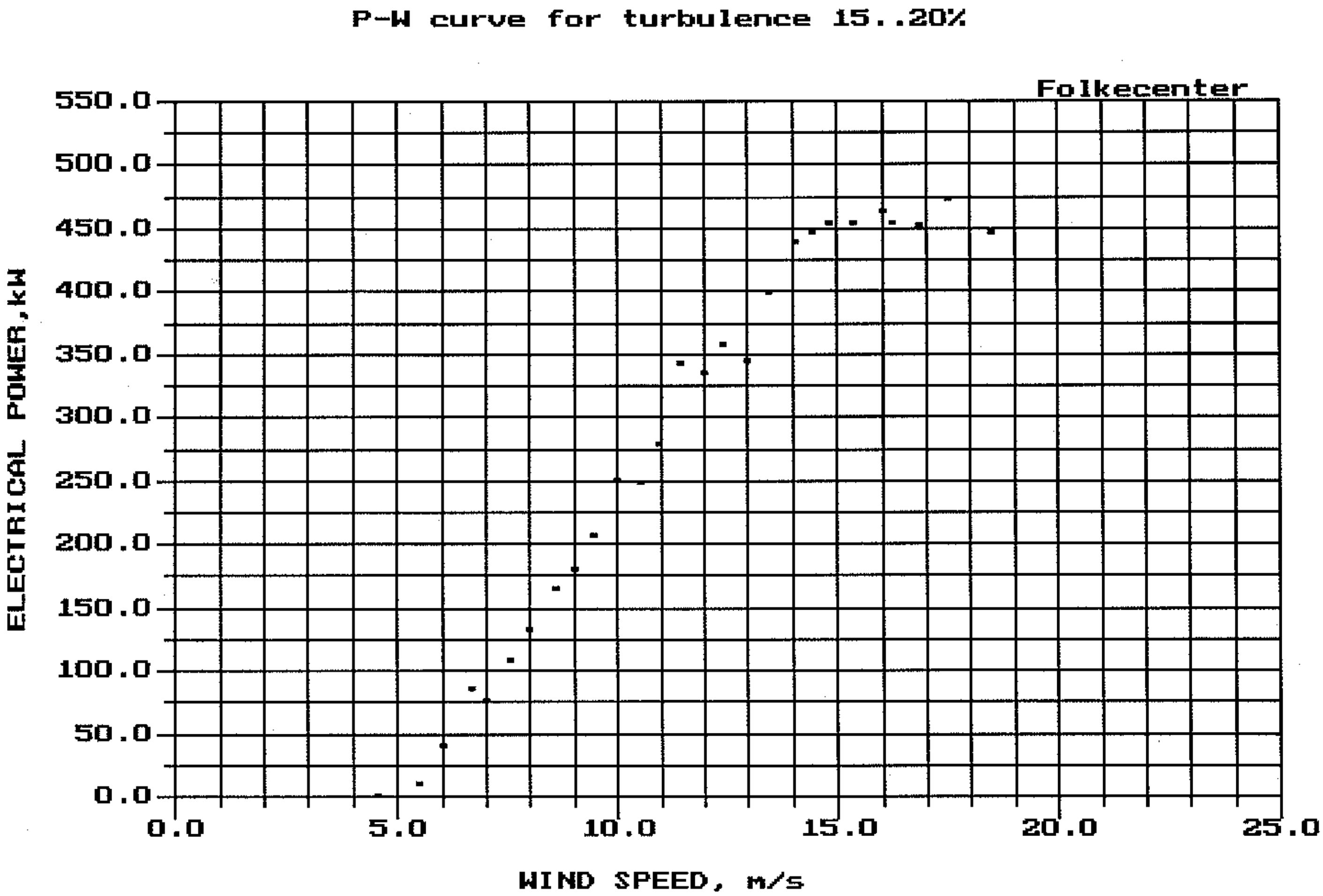

Fig.32. The bin-averaged power curve. Wind speed turbulence 15%...20%.

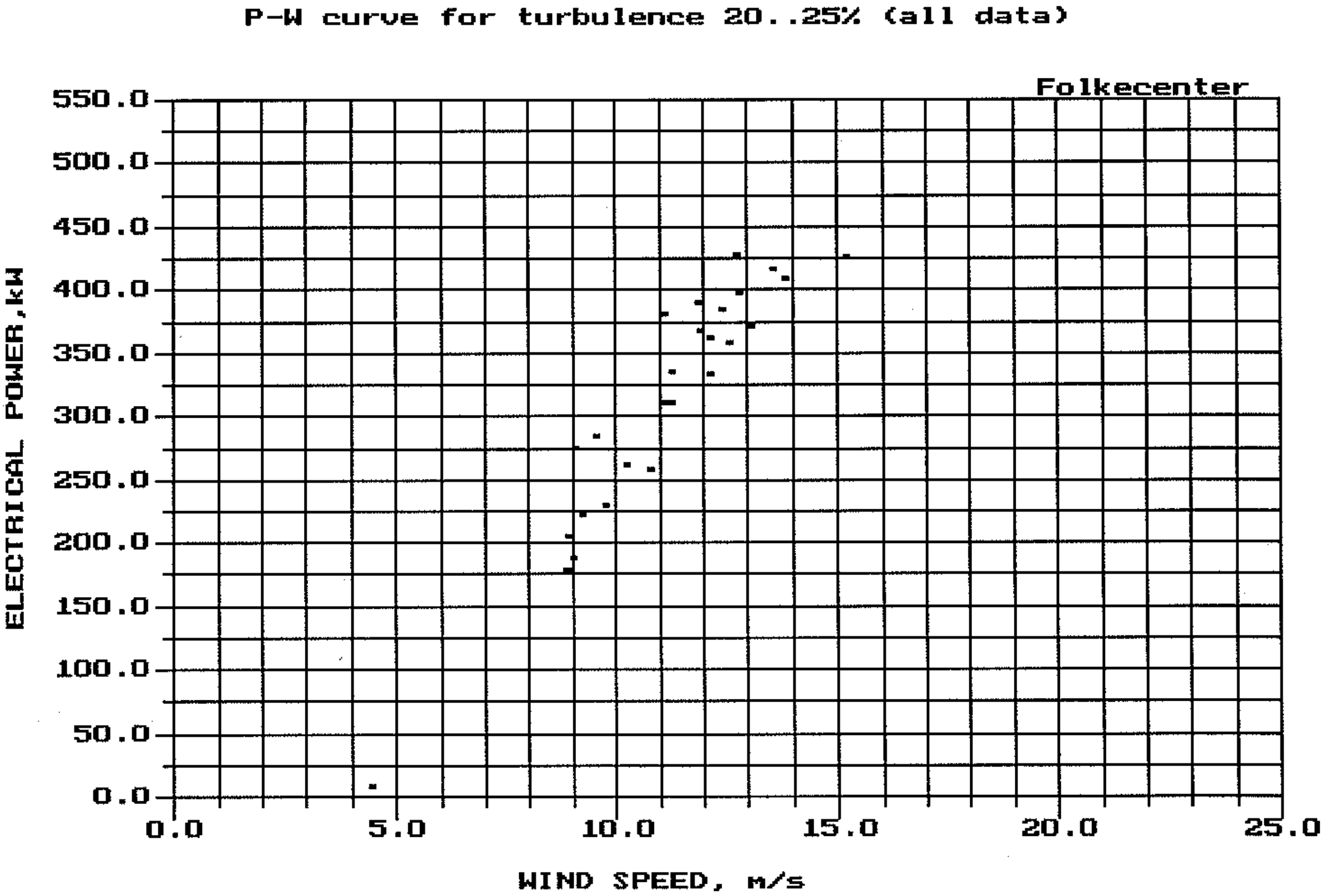

Fig.33. The power-wind speed 10 minutes averaged data. Wind speed turbulence 20%...25%.

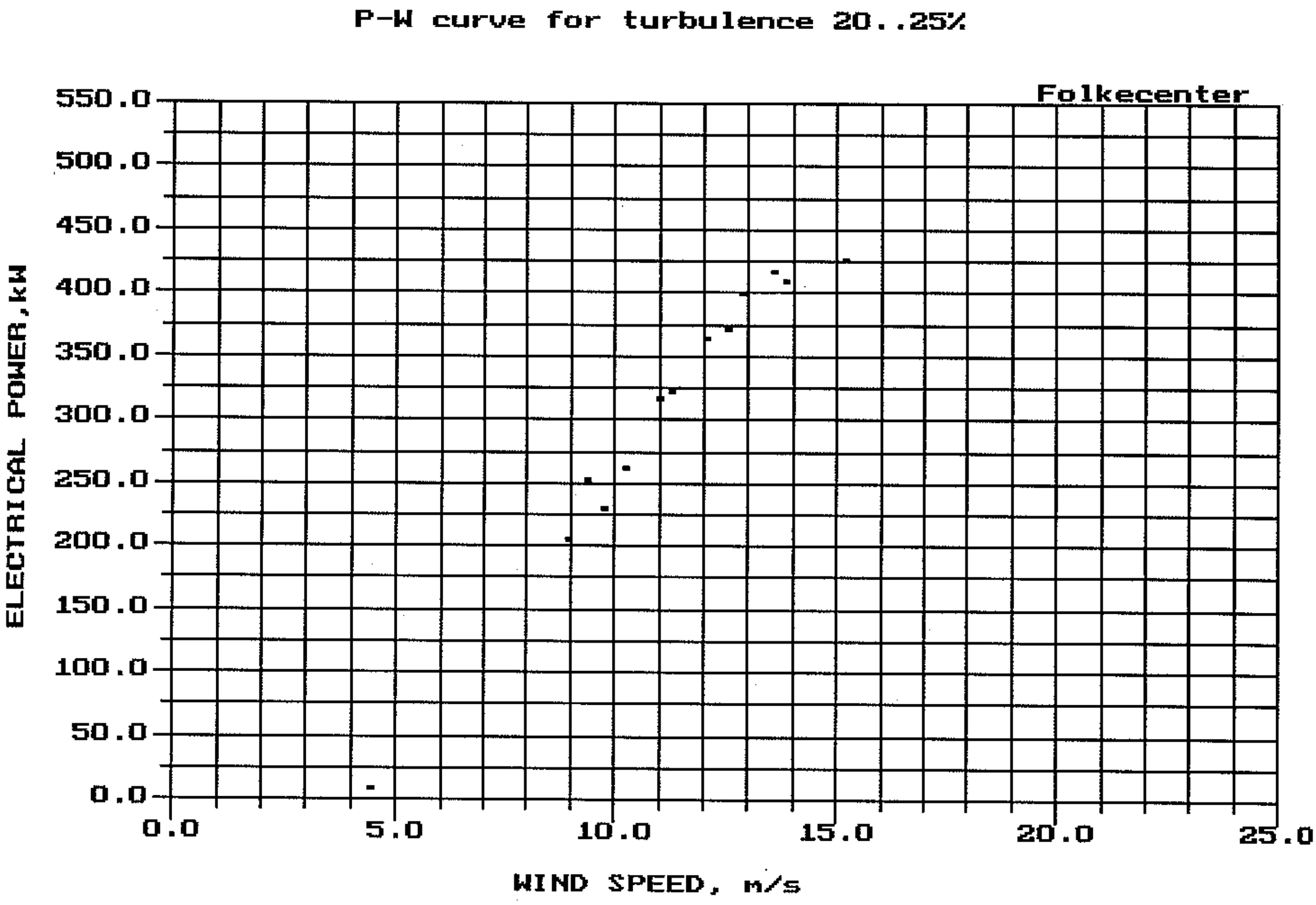

Fig.34. The bin-averaged power curve. Wind speed turbulence 20%...25%.

Table 2

Turbulence 5... 10%

BIN nr.	BIN interval	BIN mid-point	Data sets number	WIND SPEED,m/s	POWER kW
0	-0.25.. 0.24	0.0	1	0.00	0.0
1	0.25.. 0.74	0.5	0	0.00	0.0
2	0.75.. 1.24	1.0	1	1.19	0.0
3	1.25.. 1.74	1.5	1	1.45	0.0
4	1.75.. 2.24	2.0	1	1.99	0.0
5	2.25.. 2.74	2.5	3	2.58	0.0
6	2.75.. 3.24	3.0	2	3.08	0.0
7	3.25.. 3.74	3.5	4	3.48	0.0
8	3.75.. 4.24	4.0	2	3.92	0.0
9	4.25.. 4.74	4.5	4	4.48	1.0
10	4.75.. 5.24	5.0	12	5.08	5.3
11	5.25.. 5.74	5.5	11	5.43	14.9
12	5.75.. 6.24	6.0	11	5.98	26.8
13	6.25.. 6.74	6.5	11	6.49	53.2
14	6.75.. 7.24	7.0	17	7.03	81.1
15	7.25.. 7.74	7.5	18	7.43	97.3
16	7.75.. 8.24	8.0	12	7.98	132.4
17	8.25.. 8.74	8.5	20	8.52	169.5
18	8.75.. 9.24	9.0	23	9.04	196.3
19	9.25.. 9.74	9.5	23	9.51	231.3
20	9.75..10.24	10.0	25	10.04	264.3
21	10.25..10.74	10.5	32	10.52	291.5
22	10.75..11.24	11.0	38	11.00	324.8
23	11.25..11.74	11.5	45	11.51	351.9
24	11.75..12.24	12.0	36	12.05	382.8
25	12.25..12.74	12.5	33	12.50	404.8
26	12.75..13.24	13.0	54	13.02	426.9
27	13.25..13.74	13.5	45	13.46	442.7
28	13.75..14.24	14.0	51	14.00	458.8
29	14.25..14.74	14.5	52	14.50	468.3
30	14.75..15.24	15.0	37	14.98	473.5
31	15.25..15.74	15.5	27	15.43	476.4
32	15.75..16.24	16.0	7	15.99	478.0
33	16.25..16.74	16.5	3	16.62	477.3
34	16.75..17.24	17.0	4	17.02	472.8
35	17.25..17.74	17.5	11	17.47	463.6
36	17.75..18.24	18.0	4	17.97	452.8
37	18.25..18.74	18.5	0	0.00	0.0
38	18.75..19.24	19.0	1	19.07	427.8
39	19.25..19.74	19.5	1	19.50	448.8
40	19.75..20.24	20.0	0	0.00	0.0
41	20.25..20.74	20.5	1	20.35	424.1
42	20.75..21.24	21.0	2	21.09	397.7
43	21.25..21.74	21.5	1	21.71	422.9
44	21.75..22.24	22.0	1	22.24	409.6
45	22.25..22.74	22.5	3	22.45	418.4
46	22.75..23.24	23.0	0	0.00	0.0
47	23.25..23.74	23.5	0	0.00	0.0
48	23.75..24.24	24.0	0	0.00	0.0
49	24.25..24.74	24.5	0	0.00	0.0
50	24.75..25.24	25.0	0	0.00	0.0

3. DATA TIME TRACKS

In this chapter are presented several data time tracks sampled at 25 Hz:

-the chordwise and flapwise blade bending moments, BMCB1 and BMFB1;
-the main shaft torque and the bending moment main shaft TSL and LSM1;
-the tower torque and bending moments, TBMT, TBM1, TBM2;
-the active and reactive power, POAN and PORN;
-electrical data: voltage, current GVG and GCG.

The mechanical loads data are given in primary signals (volts), with no scaling or off-set constants done by the software. After the calibration, the data could be easily converted in physical values.

For every regime the data time tracks are simultaneously recorded so they are correlated in time.
For all the data time tracks presented here, the signals keep the same primary calibration so that a correlation between the data in different regimes could be made.

The zero setting values for the loads data are given in the table 3.

Table 3

BMCB1 blade chordwise bending	2.53
BMFB1 blade flapwise bending	2.32
LSM1 main shaft bending axis X	2.32
TSL main shaft torque	1.18
TBMT tower torque	-0.25
TBM1 tower bending axis X	-0.10
TBM2 tower bending axis Y	-0.12

Other symbols used to name the signals in the figures are:

GVG- generator voltage
GCG- generator current
POAN- active power generator
PORN- reactive power generator
SSH- generator speed

3.1 Normal regimes- low power, medium power, stalling

The figures 35...37 show the data time tracks for normal operation regimes with different wind conditions (table 4).

Table 4

REGIME	Average power kW	Average wind speed, m/s	Wind direction degrees
LOW	12	5.2	164
MEDIUM	270	10.3	267
STALLING	420	19.0	225

The mechanical loads are, as expected, increasing with the power level. To mention the important eigenfrequency motion of the blades in chordwide direction in the stalling regime.

3.2. Special regimes

A cut-in to the grid regime is shown in fig. 38. The average wind speed is 5.6 m/s and the wind direction 180 deg.

In fig. 39 one sees the data during the first seconds of an aerodynamic brake (blades tips out). The average wind speed is 10 m/s and the wind direction is 265 degrees.

An emergency stop procedure is shown in fig. 40. The average wind speed is 7.3 m/s. The wind turbine is stopped in 11 seconds in the interval 1.25 ...12.20 sec. The remanent speed record seen in fig. 40 after the stop of the wind turbine at 12.20 sec is given by the digital counting scheme of the generator speed measurement. The reactive power still persists some seconds after the disconnection of the grid switch. It is explained by a self excitation phenomenum with the capacitors connected to the induction generator outputs.

Finally, in fig. 41 one gives the electrical data tracks for a low power regime. One sees how the thyristors system controls the generator voltage in order to minimize the generator losses in this regime.

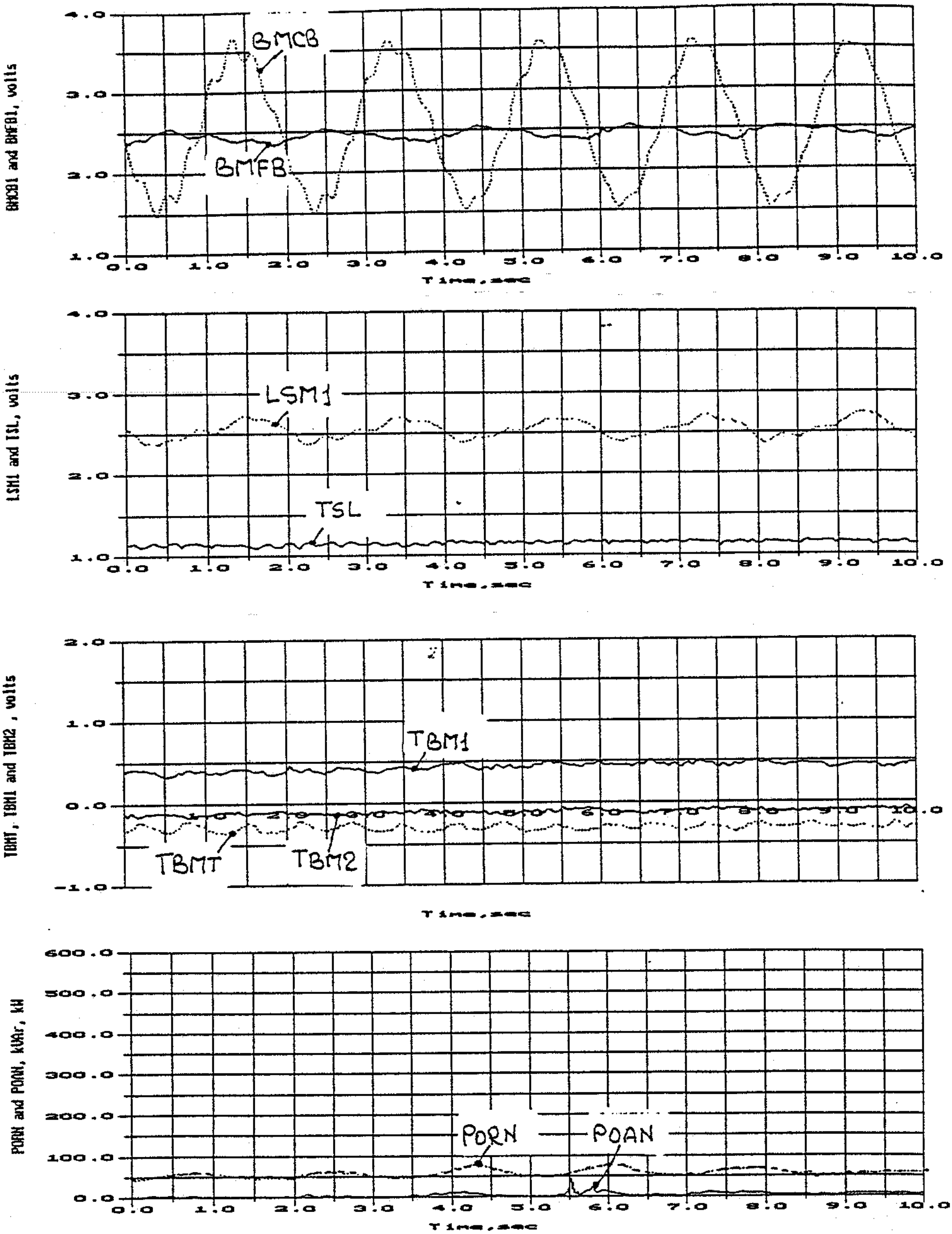

Fig.35. Data time tracks of a low power regime

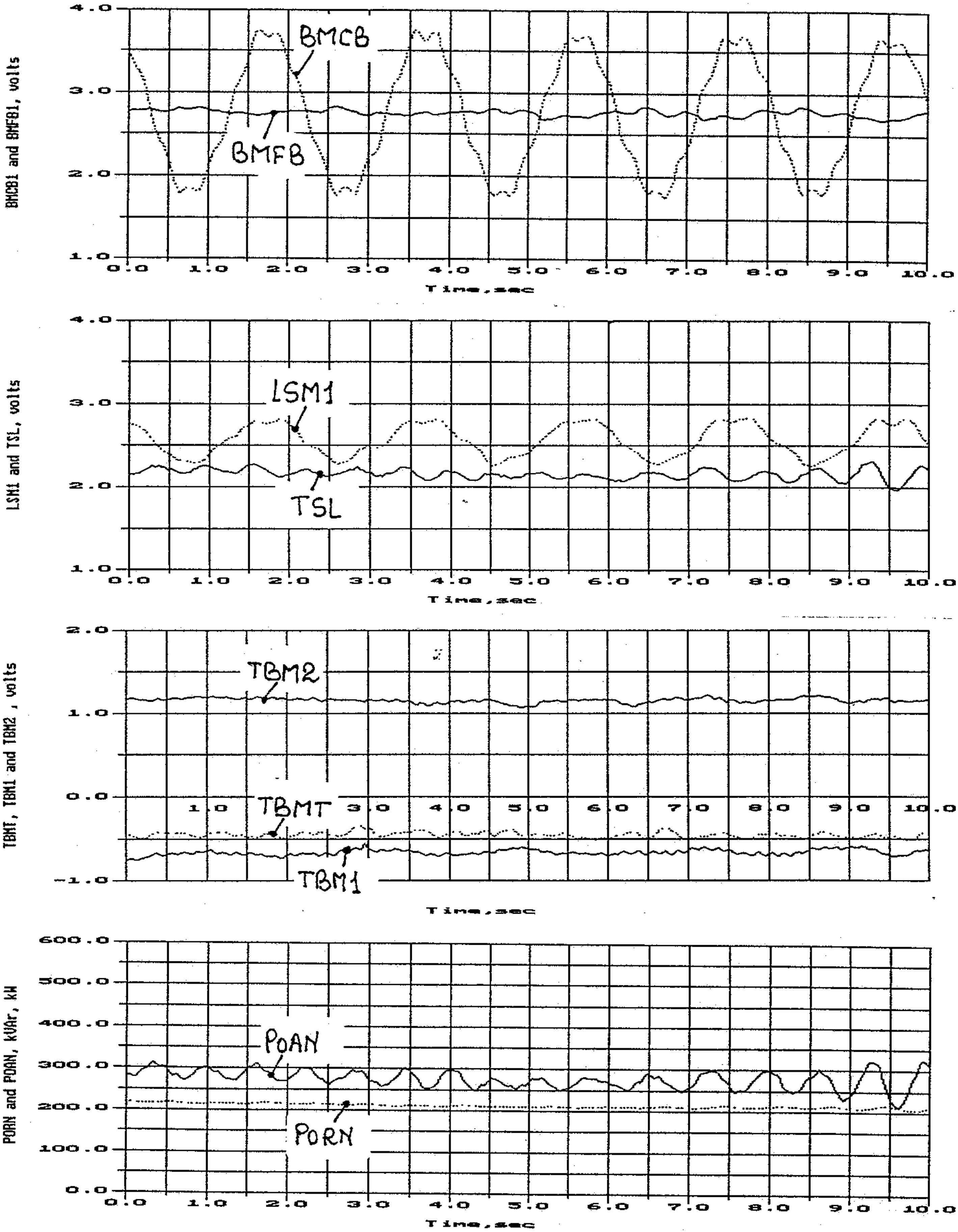

Fig.36. Data time tracks of a medium power regime

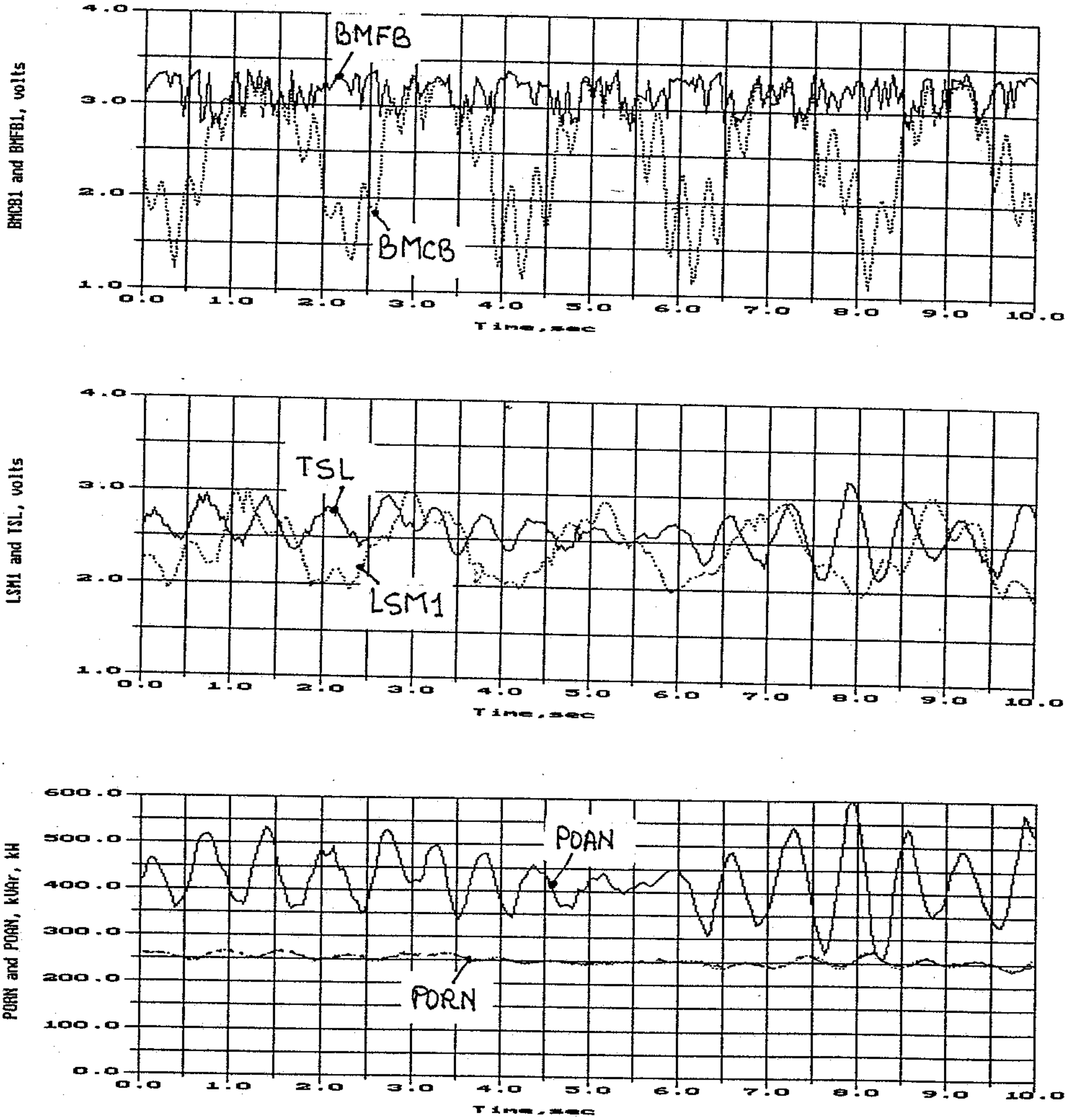

Fig.37. Data time tracks of a stalling regime

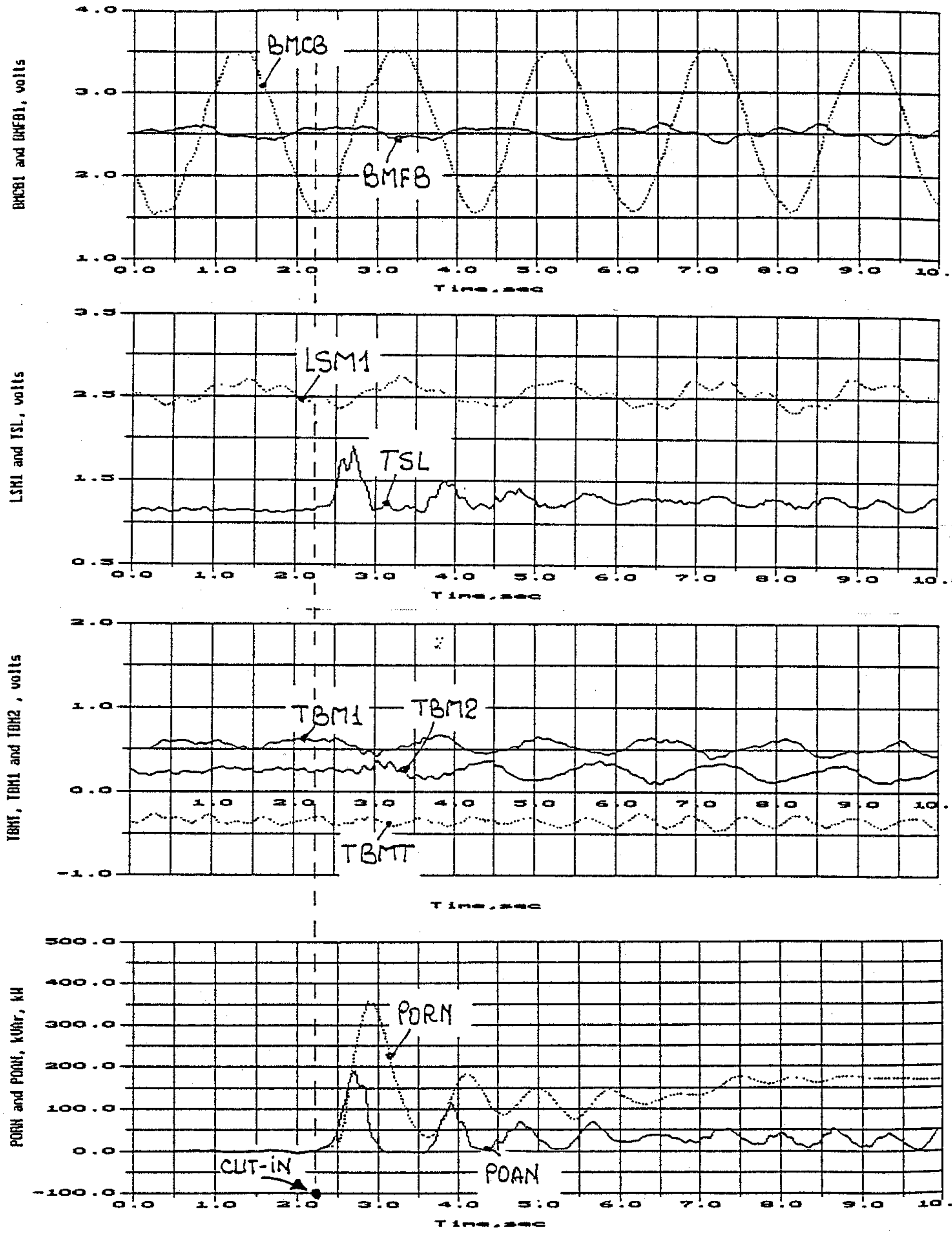

Fig.38. Data time tracks for a cut-in to the grid regime

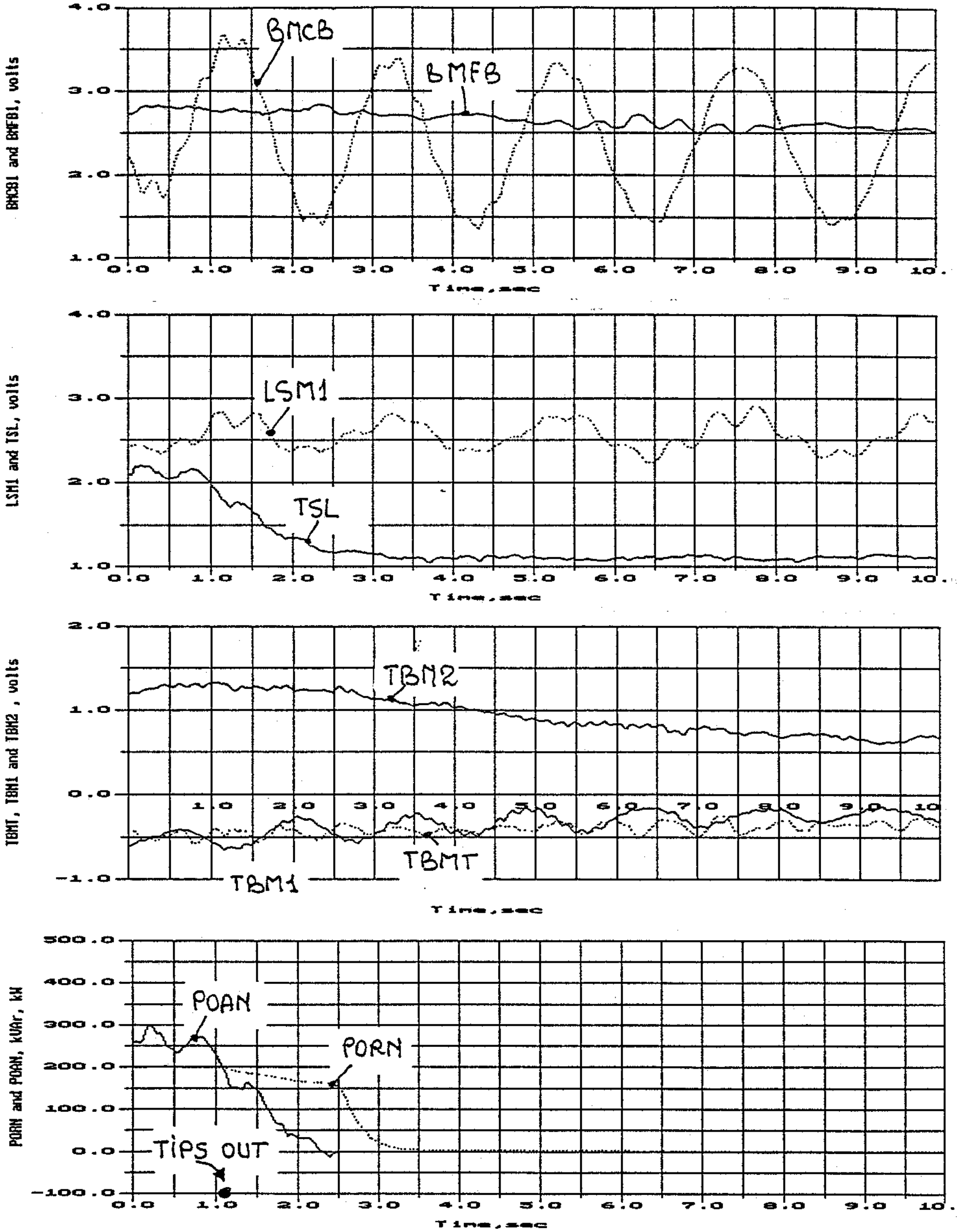

Fig.39. Data time tracks for an aerodynamic brake regime

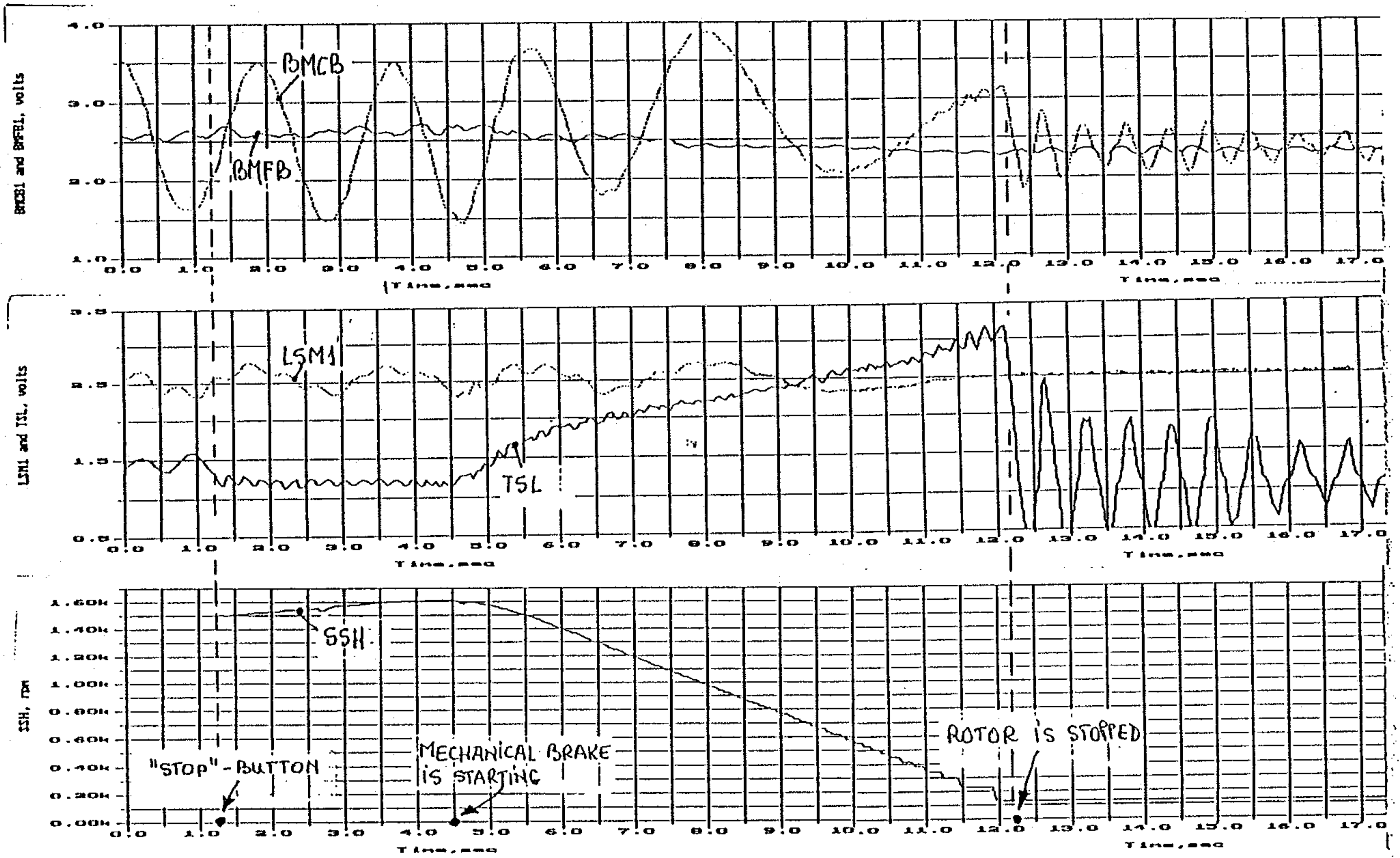

Fig.40 a. Data time tracks for an emergency stop regime

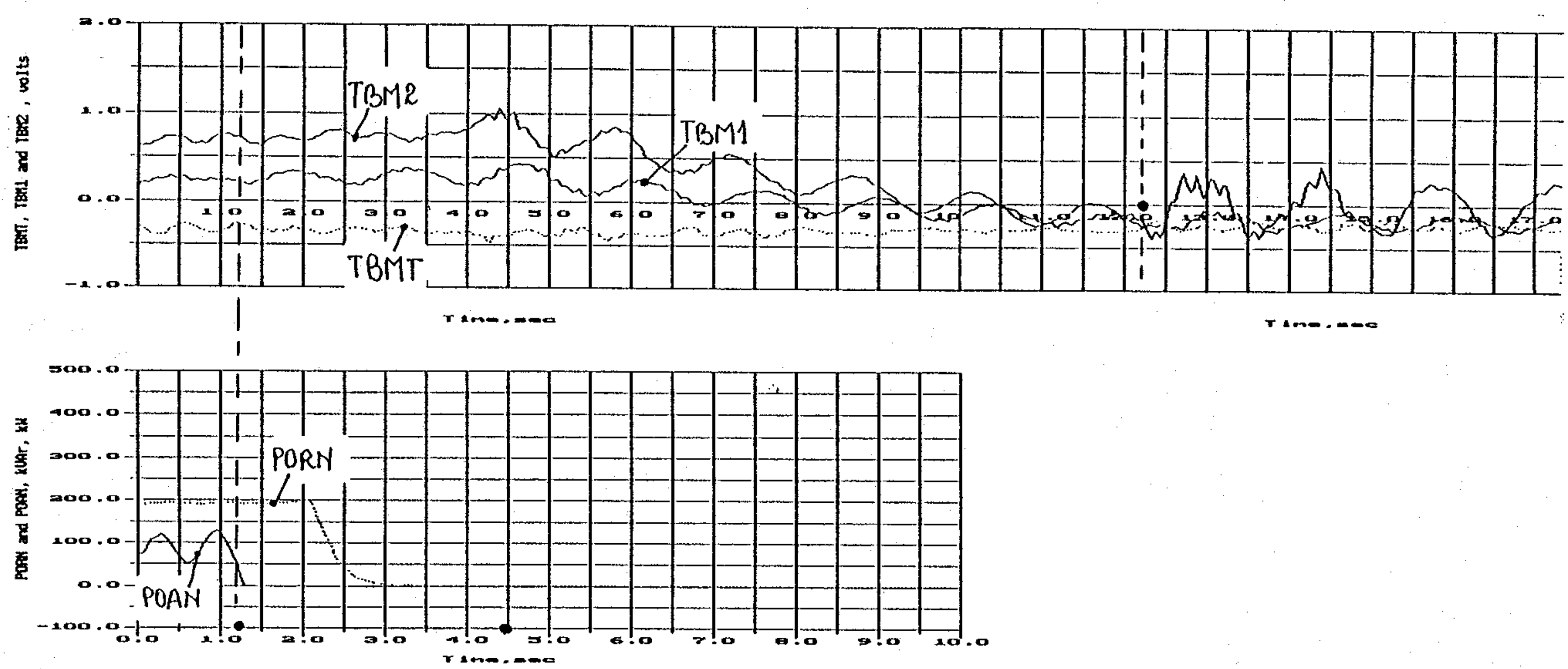

Fig.40 b. Data time tracks for an emergency stop regime

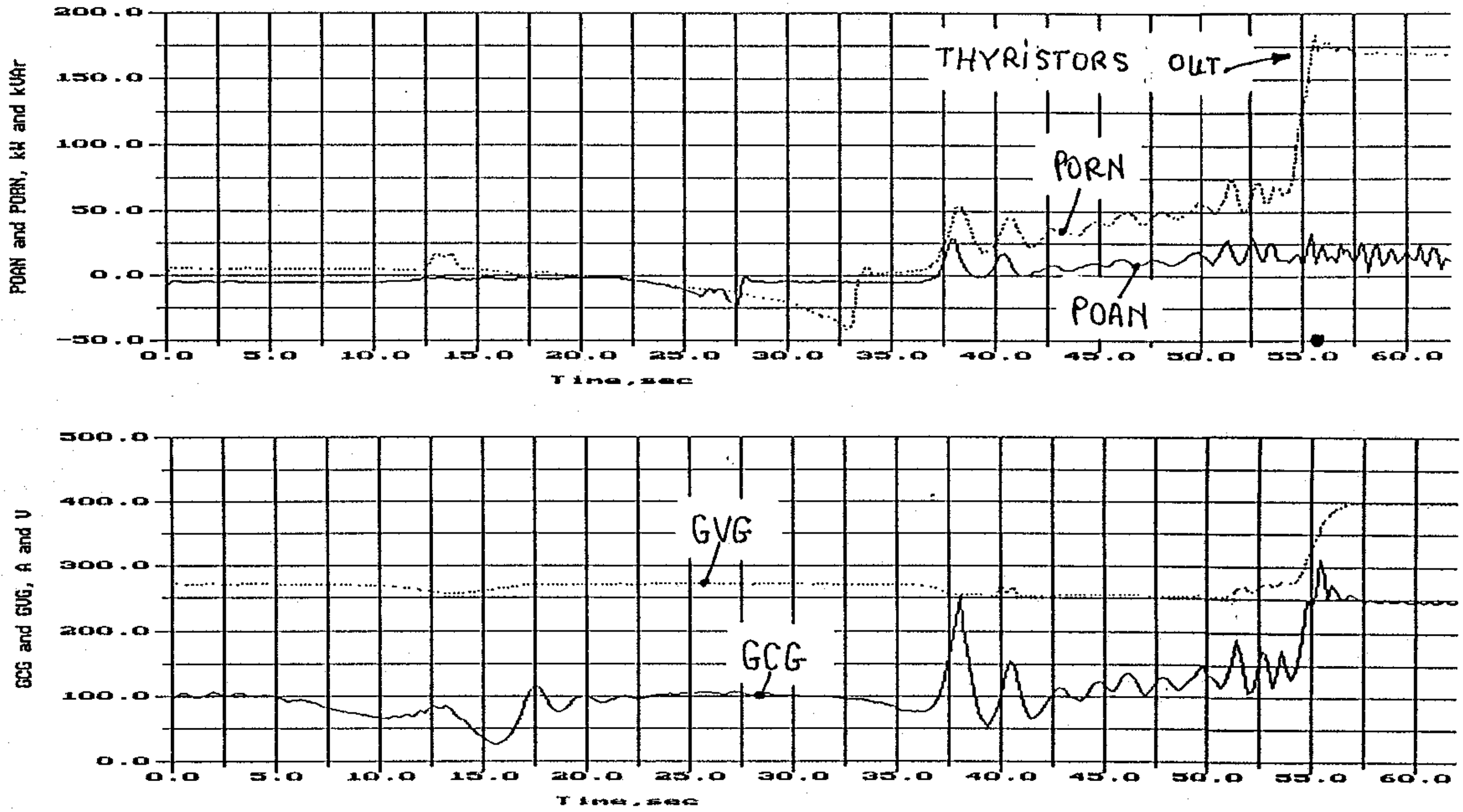

Fig.41. Data time tracks for an electrical regime with thyristors

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