Technical University of Denmark

Nacelle anemometry on a 1MW wind turbine: Comparing the power performance results by use of the nacelle or mast anemometer

Antoniou, Ioannis; Friis Pedersen, Troels

Publication date:
1997

Document Version
Publisher's PDF, also known as Version of record

RISØ DK97020-18

Risø-R-941(EN)

Nacelle Anemometry on a 1MW Wind Turbine:

Comparing the power performance results by use of the nacelle or mast anemometer

Ioannis Antoniou, Troels Friis Pedersen

Risø National Laboratory, Roskilde, Denmark
August 1997

Nacelle Anemometry on a 1MW Wind Turbine:

Comparing the power performance results by use of the nacelle or mast anemometer

Risø-R-941(EN)

RISO-R--941(EN)

Ioannis Antoniou, Troels Friis Pedersen

Risø National Laboratory, Roskilde, Denmark
August 1997

Abstract

The report describes measurements carried out on the ELKRAFT 1MW wind turbine in the period from week 46 / 1994 to week 10 / 1997. The correlation between the mast and the nacelle anemometer is investigated and the result of the power curve measurements is presented as a function of both the mast and the "corrected" nacelle anemometer. The scope of this is to gain a better understanding on the merits and limitations of the use of the nacelle anemometer as an alternative to the mast anemometer for the verification of the turbine's power curve and the calculation of the annual energy production. Data collected from three phases of operation and two nacelle anemometer height positions is shown and compared with each other in the present report. During the first phase the turbine blades are set at a pitch angle of +0.5° (nacelle anemometer at 1.2m height). During the second phase the turbine blades are also set at a pitch angle of +0.5° and a new yaw condition is introduced in order to reduce the turbine's yaw error (nacelle anemometer at 1.2m height). Finally, during the third phase, the pitch angle of the blades is set to -1.0° and vortex generators are placed in the inner part of the blades (nacelle anemometer at 1.2m and 3m height). Following the above analysis conclusions, concerning the limits on the use of the nacelle anemometer as an alternative for the power curve measurements, will be drawn.

The work presented has been funded by the following projects:

- VIM 03639-00(internal proj. number) ELKRAFT 1MW Wind Turbine
- JOR-CT95-0064 (EWTSII)
- JOR-CT96-0114 (Power Performance Assessment)

The report has passed an internal review at The Test Station for Wind Turbines performed by:

Sten Frandsen

ISBN 87-550-2323-1

ISSN 0106-2840

Information Service Department, Risø, 1997

DISCLAIMER

Contents

1. Introduction

In the present report the use of the nacelle anemometer as a tool for verifying a turbine's power curve is examined. This research is based on the results of the power curve measurements that have been carried out on the ELKRAFT 1MW stall-regulated wind turbine. From these results the relation between the nacelle and the cup anemometer is initially established from data of a 90° wide measurement sector. Following that three objectives are defined:

- The first objective is to investigate whether for the same rotor settings the relation between the nacelle and the mast anemometer (established with data from the 90° power curve measurement sector) is also valid for other sectors. This is equivalent to examining whether the power curve (as a function of the corrected nacelle anemometer) can be reproduced for other sectors and different data sets. It gives also evidence whether the nacelle-mast relation defined within a measurement sector in flat terrain is still valid and thus transferable to another terrain type.
- The second objective is to investigate whether and how the relation between the mast and the nacelle anemometer is influenced by the specific position of the nacelle anemometer.
- The third objective is to investigate whether different rotor settings affect the relation between the nacelle and the mast anemometer and if so how the use of a wrong relation would affect the correct presentation of the power curve and the evaluation of the annual energy production (a.e.p.).

The result should be a better understanding on the merits and limitations from the use of the nacelle anemometer as an alternative to the mast anemometer for the verification of the turbine's power curve and the calculation of its a.e.p..

The rules for measuring the power curve of a wind turbine in flat terrain are well established. Among the demands is the use of a cup anemometer mounted on the top of a met. mast at preferably a distance of 2.5 rotor diameters from the turbine. On many occasions however, mainly due to contractual obligations of the manufacturer or the wind park developer, there is a need to verify the individual turbine's power curve. and -as an alternative- the use of the nacelle anemometer has been suggested.

This subject has resulted in many discussions and disputes. The relation between the response of the nacelle and the mast anemometer must as a rule be established during the power curve measurements in flat terrain or where site effects are known. Then the question to be answered is whether this relation can be used to verify another turbine's power curve which is installed elsewhere, alone or within a wind park. It is understood that the turbine should be of the same make and type. For the turbine manufacturer or the wind park developer this method has an obvious economic interest as it reduces the costs involved with the assessment of the turbine's power curve and the related guarantied a.e.p..

The wind speed registered by the nacelle anemometer and thus its relation to the mast anemometer is mainly expected to be influenced by two factors, the placement of the anemometer on the nacelle and the retardation of the flow due to the power extracted from the wind. For the placement of the anemometer on the nacelle , there are not generally accepted instructions regarding the height from- and the position on the nacelle. The presence of the nacelle influences the flow and can easily result in either an acceleration or retardation of the wind speed at the position where the cup anemometer is mounted. In Ref. 1 some preliminary mounting instructions can be found, but they are not yet either well documented or generally accepted. The retardation on the other hand of the flow due to the energy extraction is as known a function of the wind speed (provided that the rotor settings remain unchanged). Since this relation is not linear, one expects that neither is the relation between the mast and nacelle anemometer. This relation is in Ref. 2 and 3 and as well as in other private communications of the authors presented as a linear one with a slope either higher or lower than unity which implies either retardation or acceleration of the local flow relative to the incoming. In Ref. 4 the relation is not linear and it is partly below and partly above unity. The previously mentioned results show clearly the degree of complexity of the flow around the nacelle

Data collected from three phases of operation and two nacelle anemometer height positions will be shown and compared with each other in the present report. During the first phase (week 46/1994 to week 10/1995) the turbine blades are set at a pitch angle of +0.5° (nacelle anemometer at 1.2m height). During the second phase (week 13/1995 to week 25/1995) the turbine blades are also set at a pitch angle of +0.5° and a new yaw condition is introduced in order to reduce the turbine's yaw error (nacelle anemometer at 1.2m height). During the third phase (week 46/1995 to week 10/1997), the pitch angle of the blades is set to -1.0° and vortex generators are placed in the inner part of the blades (nacelle anemometer at 1.2m height) while during the last measurement period (week 41/1996 to week 10/1997) the nacelle anemometer was placed at 3m height above the nacelle. Schematically this is presented in the following table

Measurement phase→	1	2	3a	3b
Pitch settings	+0.5°	+0.5°	-1.0°	-1.0°
Nacelle anemometer height	1.2m	1.2m	1.2m	3.m
Yaw error at 10m/s	+12	+7	+7	+7
VG on the blades	no	no	yes	yes

Following the above analysis conclusions, concerning the limits on the use of the nacelle anemometer as an alternative for the power curve measurements, will be drawn. Data collected from three phases of the operation of the turbine will be shown and compared with each other in the present report.

2. Description of the wind turbine

A picture of the turbine can be seen in Fig. 2-1. The technical specifications of the wind turbine relevant to the investigation are give below

Technical specification for the ELKRAFT 1MW wind turbine		
Rotor	Power regulation	Stall
	No. of blades	3
	Rotor diameter	50 m
	Swept area	1963 m^2
	Hub height	55 m
	Rotor speed	23.13 rpm
	Tilt	3.5 °
	Coning	0.0 °
	Tip angle	phase2: 0.5 ° ,phase3 and 5 : -0.5°
	Direction of rotation (from upwind)	Clockwise
Blades	Manufacturer	LM
	Construction	Cantilevered
	Material	Glassfiber reinforced polyester
	Blade length	24 m
	Profiled blade length	20 m
	Root chord	2.3 m
	Tip chord	55 mm
	Twist	15 °
	Blade profiles	FFA-W3 (inner radius) and NACA 63-4xx (outer radius)
	Air brakes	Hydraulic controlled pivotal blade tips
	Weight	3300 kg
Gearbox	Type	Planet combined with a three stage gear box
	Exchange ratio	1:65.82
	Effect	1100 kW
	Type	Asynchronous
	Weight	14500 kg (without oil)
Generator	Number	Two coupled in line on the same shaft

Table 2-1 Technical description of the ELKRAFT 1MW

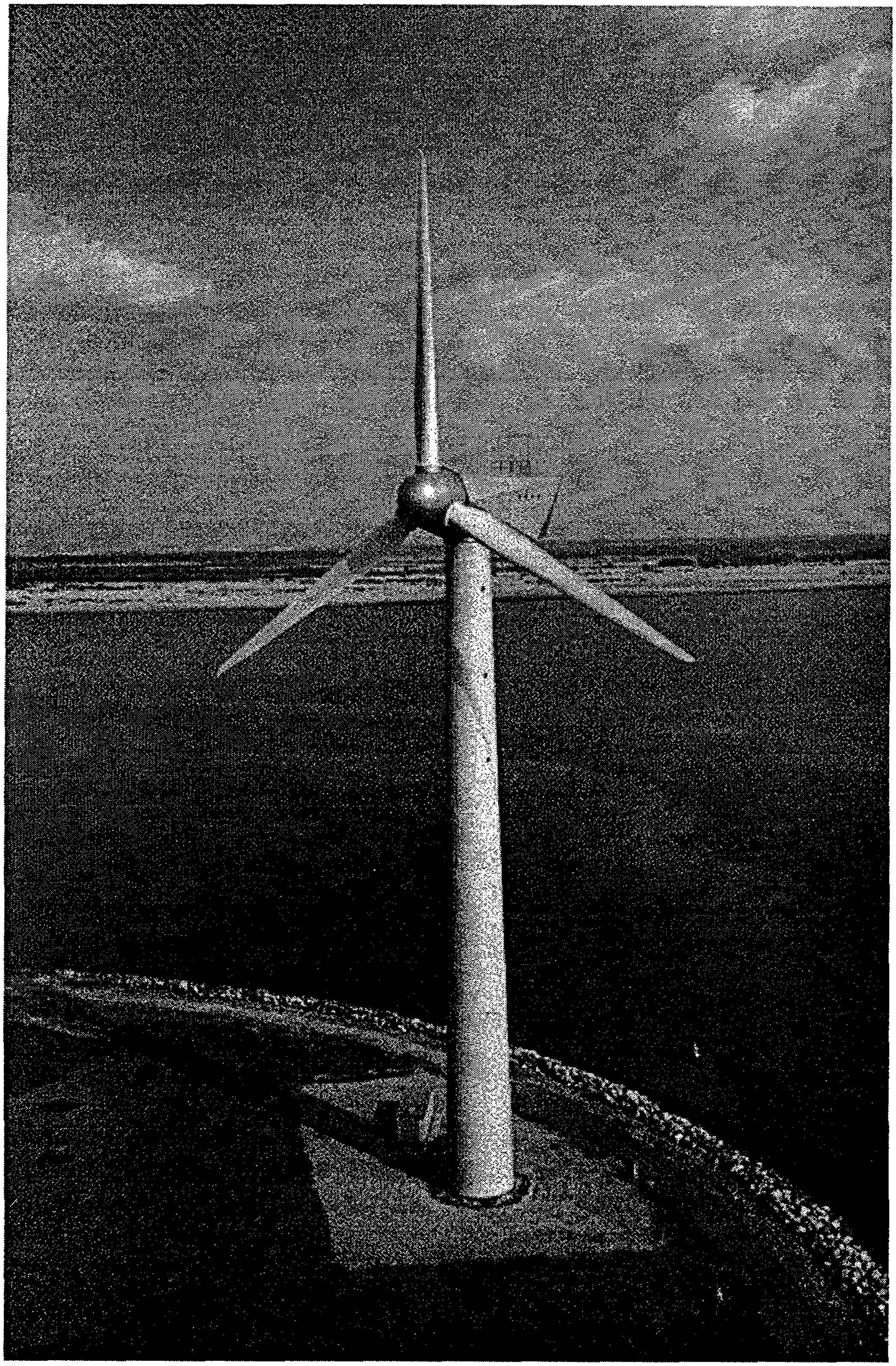

Figure 2-1 The ELKRAFT 1MW wind turbine

3. Description of the test site

3.1 Location

Address of the turbine: Avedøre Værket, Hammer Holmen,.2650 Hvidorve. The location of the turbine is shown in Figure 3-1.

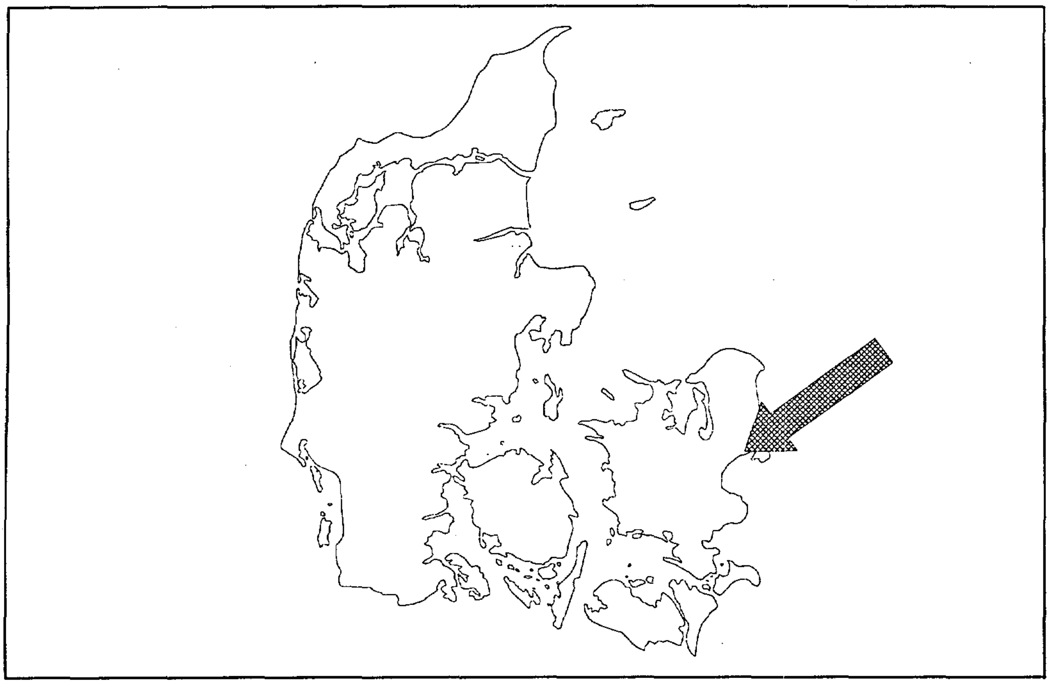

Figure 3-1 Geographic location of the wind turbine

3.2 Terrain description

A topographic map of the test site is shown in Figure 3-2 and a detail of the wind turbine location together with the measurement sector is shown in Figure 3-3. In Figure 3-4 and Figure 3-5, the site seen from the nacelle of the turbine (covering almost 360°) is shown. In Figure 3-5 the cup anemometer at 1.2m on top of the nacelle is seen.

The sector used for the power curve measurements is from 181.5° to 271.5° for the first and the second phase data and from 165° to 265° for the third phase data. The direction defined by the met mast and the turbine is 270°→90° with the mast located west for the turbine. The distance between the mast and the turbine is 2.56D. The measurement sector is seen to be displaced by almost 45° to the south relative to the requirements of Ref. [6]. This is done in order to satisfy the requirements for the measurement sector posed by Ref. [6]. The terrain around the turbine is flat and in the measurement sector there are no roughness elements of importance except for a wave brake of stones into the sea with an estimated height of one to two meters. In the north of the measurement sector and up to 330° the following big obstacles can be found:

→ a ship dock, a crane and ships of varying size

→ the Avedøre power plant

→ high banks of coal

→ big fuel tanks and

→ deposits of cinder

From 330° and up to 15°, the terrain becomes more uniform with smaller irregularities. From 15° to 180° the turbine neighbors to the sea and at a distance of some hundred meters there is a recreation rural area without any big terrain irregularities. The area is only a few meters higher than sea level. It should also be mentioned that the ground where the power plant and hence the turbine is located is reclaimed at a later moment from the neighboring ground to the north and therefore this ground is at a higher level relative to the neighboring one.

Due to the above the test site does not satisfy some of the demands for power curve measurements imposed by Ref. [6]. In Table 3-1 is shown which of the requirements of Ref. [6] are satisfied by the used test sector. The sector used for the power curve measurements and nacelle anemometer calibration is flat and site effects are not expected to be present.

Distance	*Sector*	*Slope of plane*	*Terrain variations*
0- 5 D	360°	< 3% (yes)	0.07 D (no)
0-10 D	360°	<5 % (yes)	0.1 D (no)
0-20 D	measurement sector	<7 % (yes)	0.2 D (yes)
0-40 D	measurement sector	roughness length	<3 cm (yes)

Table 3-1 Requirements satisfied by the test site

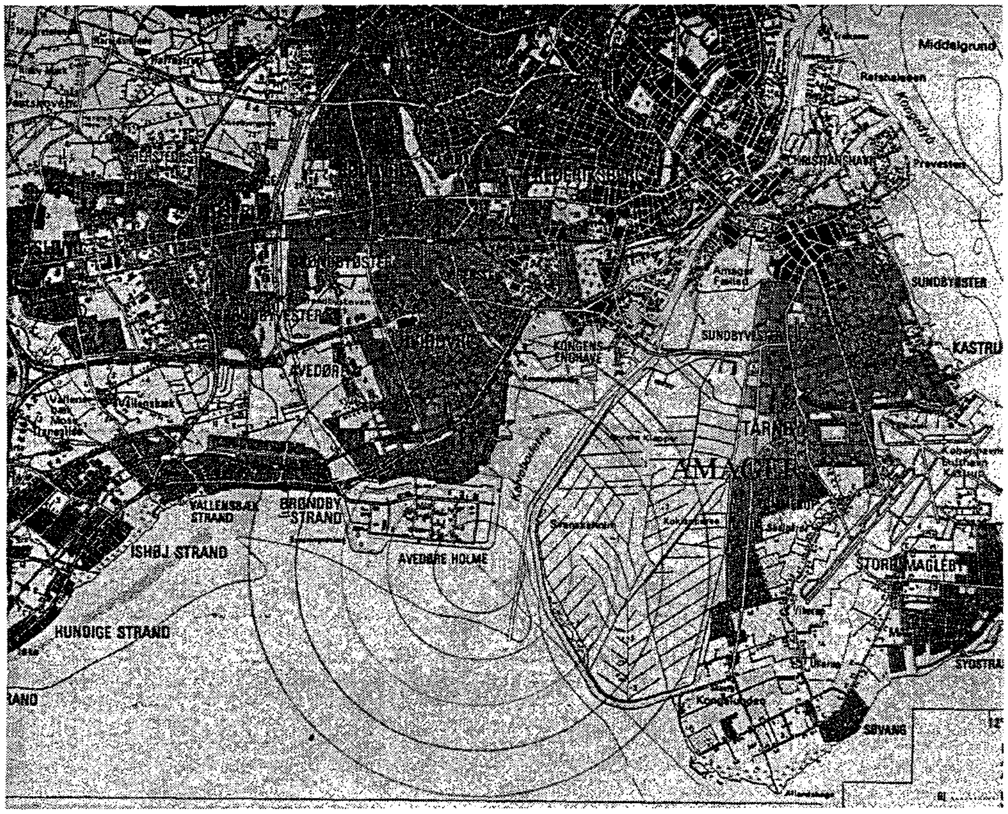

Figure 3-2 Topographic map of the test site around the turbine (distance bet. circles: 1km)

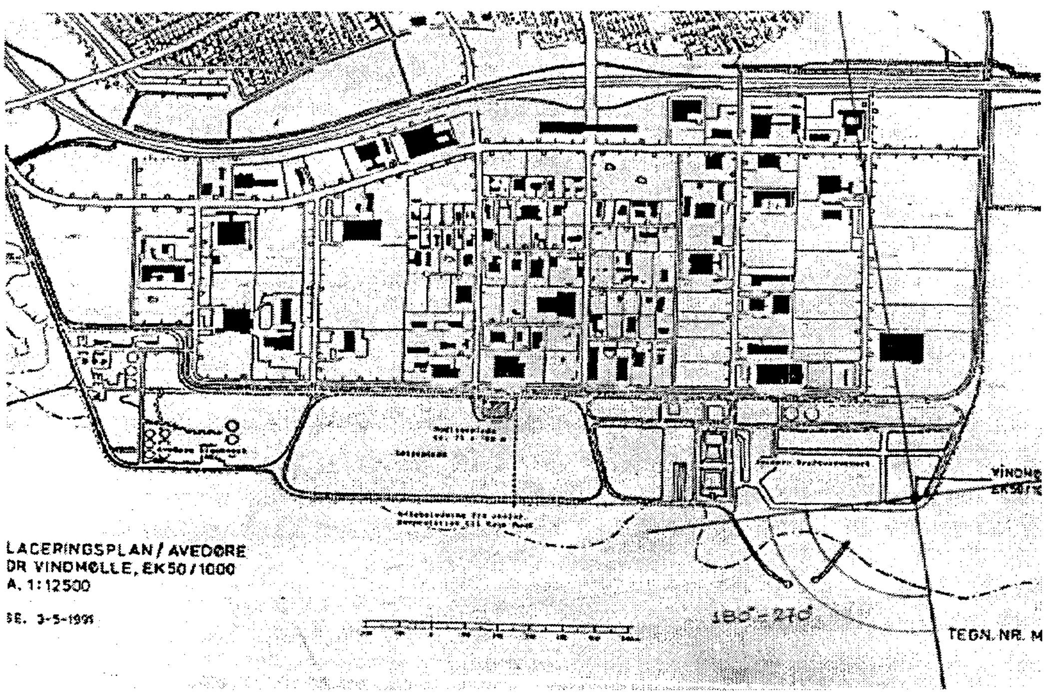

Figure 3-3 Detail of the wind turbines surroundings and the measurement sector

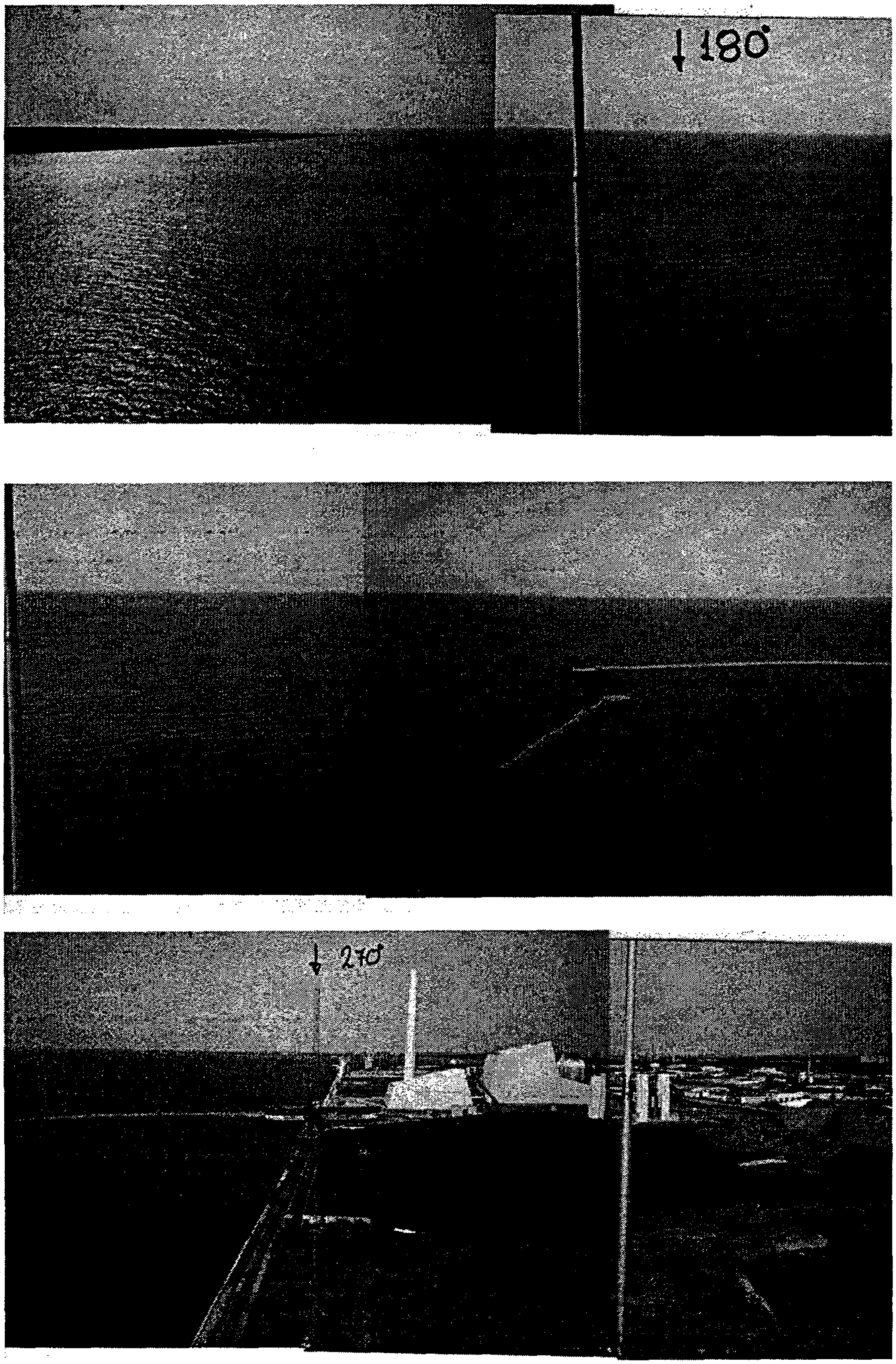

Figure 3-4 The test site from 55 m. height, seen from the top of the nacelle

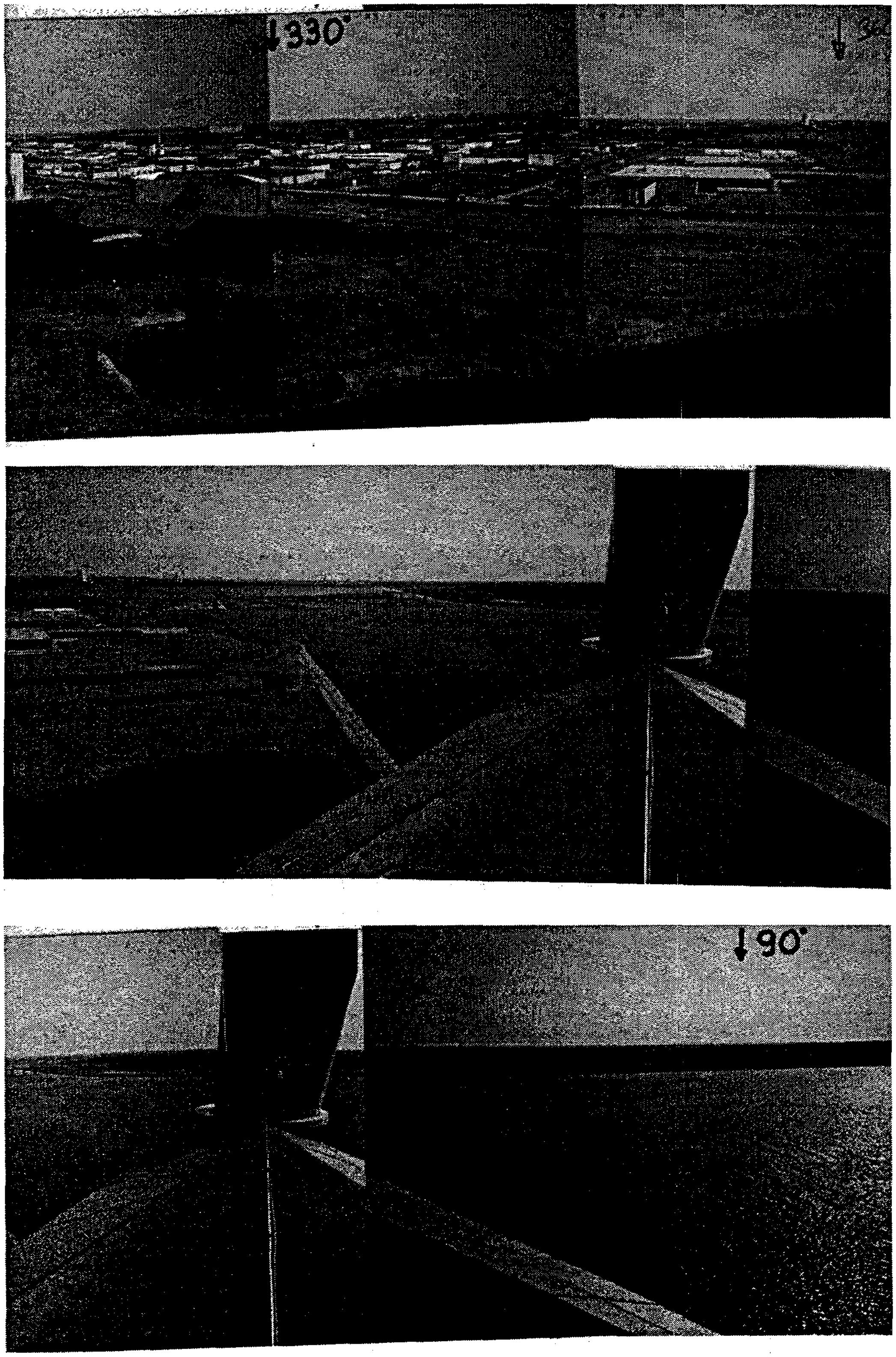

Figure 3-5 The test site from 55 m. height, seen from the top of the nacelle (cont.)

4. Instrumentation

In the following the measurement setup related to the measurements reported in this document is presented. Measurements of meteorological parameters, and turbine operational parameters are reported.

4.1 *Measured parameters*

The measured parameters relevant to this report are shown in Table 4-1 together with their name in the measurement setup and their sampling frequency. The wind turbine is operated as stall regulated. A full description of the measurement setup can however be found in Ref. [7]. The electrical power is measured on each generator individually. The two signals are added together to calculate the turbine's electrical power. The power consumption of the turbine is not subtracted as recommended in Ref. [6] and [8].

Position	Name and channel number in the measurement setup	Parameter	Sampling frequency
Met. Mast	Cup55(57)	Wind speed at 55m. height	4 Hz
	Cup75(56)	Wind speed at 75m. height	4 Hz
	Cup35(58)	Wind speed at 35m. height	4 Hz
	Wdir(64)	Wind direction at 53m. height	4 Hz
	Tempair(65)	Air Temperature at 53m. height	1 Hz
Nacelle	RPM(67)	Rotor rotational speed	4 Hz
	Cupkab(59)	Wind speed at 1.2m and 3m above the nacelle	4 Hz
	KontactG1	Status signal generator no. 1	32 Hz
	KontactG2	Status signal generator no. 2	32 Hz
Kiosk	Barom(60)	Atm. Pressure	1 Hz
	Nedbr(61)	Rain	1 Hz
	Effekt(68)	Electrical power	32 Hz

Table 4-1 Measured parameter list

The instrumentation of the wind turbine with sensors and transmitter boxes can be found in Ref. [5].

5. Comparison procedure

5.1 Choice of data

The following data are used for the power curve measurements and the comparisons between mast and nacelle anemometers:

- Data form the sectors between 181.5° and 271.5° (first and second phase) and between 175° and 265° (third phase). These sectors are used for the original power curve measurements and are open water sectors with land present at a longer distance from the turbine. The slight translation of the measurement sector in the third phase is due to the temporary formation of a cinder bank between the turbine and the met. mast and is not consider to have any influence on the results. The cinder is now removed.
- The power curve as function of the corrected response of the nacelle anemometer is, except for the above sectors, shown also for the sectors
  1. 271.5° to 331.5° (turbine in the wake of the power plant)
  2. 330° to 360° (sector with a different roughness length)
  3. 110° to 180° (open water and uniform low elevation land).
- Bit channels KontaktG1(43) and KontaktG2(44) must be equal to one (then the turbine's two generators are connected to the grid for the whole duration of the run).
- All turbulence intensities are included
- Rain weather data are included

5.2 Correction of data

The electrical power is corrected for a standard air density of 1.225 kg/m^3 which corresponds to a standard temperature of 15 °C (dry air) and a pressure of 1013 hPa.

The air density is calculated from measurements of the air temperature and pressure:

$$\rho = 1.225 \frac{288.15}{273.15 + t} \cdot \frac{B}{1013.3}$$

where t measured temperature in °C

B measured air pressure in mBar

The electrical power is corrected in the following way:

$$P = P_m \cdot \frac{\rho_o}{\rho}$$

where the subscript o refers to the standard air density and m to the measured values.

After the data correction, the wind speed and the electrical power are sorted following the "Method of bins" as used in Ref.[8].

6. Results of the measurement program

6.*1 The power curves*

The power curves of the turbine for all the three measurement phases are given as a function of the mast anemometer at 55m height (hub height). The curves are presented as the mean bin data values of ten-minutes periods, corrected for temperature and pressure (T=15°C and P=1013.3 hPa). In Figure 6-1 the turbine's mean yaw error is shown for the three phases.

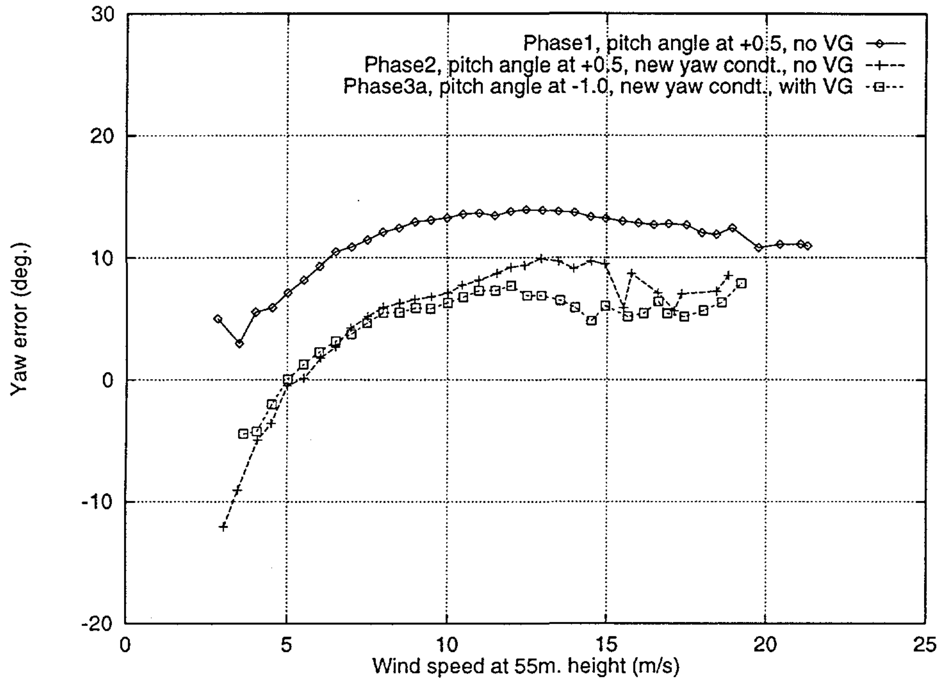

Figure 6-1 The yaw error for the three power curves

In order to correct the initial yaw error, the turbine's wind vane was turned 12° in the anti-clockwise direction. This resulted in a reduction in the yaw error by approximately 7°. Referring still to Figure 6-1, the data from phase2 and phase3a follow well each other up to 12m/s after which deviations are observed. It is not clear whether these are due to scatter because of the limited data available or to the modifications of the flow field behind the rotor hub caused by the presence of the vortex generators.

In Figure 6-2 the turbine's power curves, for the three phases, are shown together with the design power curve calculated for a pitch angle equal to -1.0° [1]. The power curves from phase1 and phase2 show good agreement between them up to 7m/s and are in fact slightly better than the design power curve. Between 7m/s and 12m/s the phase2 power curve is better than the phase1 one, which can be attributed to the lower yaw error. At higher wind speeds the two power curves agree well although the phase2 curve shows a higher scatter due to the limited amount of data. The two curves are well below the design curve (result of theoretical calculations) for wind speeds between 8m/s and 17m/s. An explanation of the reduced performance of the rotor relative to the expected design curve under this configuration is that early separation of the flow occurs in the thick inner sections of the blades. Therefore it was decided to install vortex generators on these parts of the blades. The vortex generators were designed by LM which also decided their positioning on the blades.

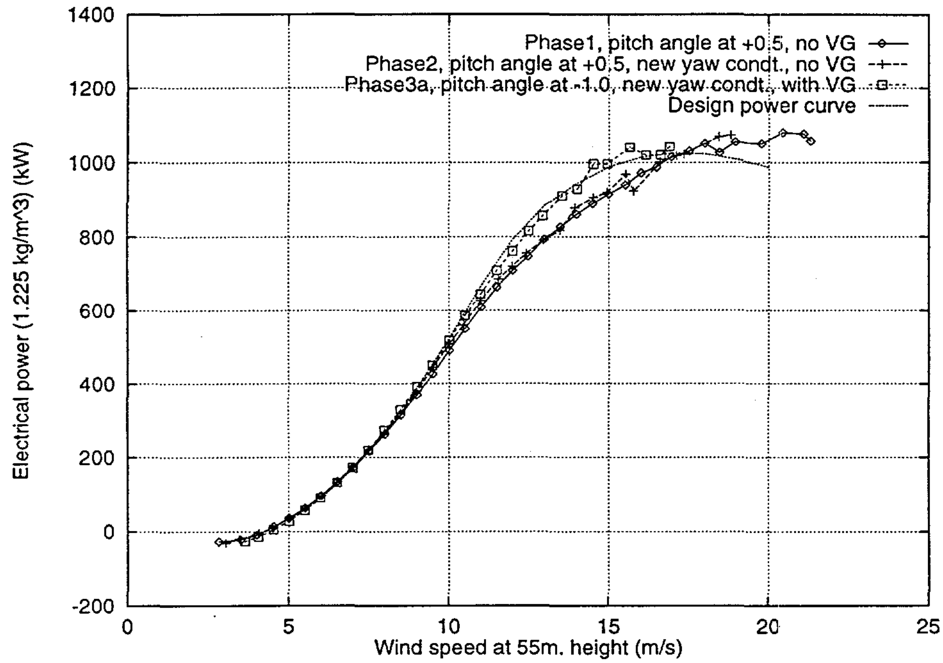

Figure 6-2 The power curves for the three phases and the calculated design curve

Regarding the phase3 curve and the design curve, good agreement exists between them up to 8m/s with the phase3 curve being slightly higher than the design one. At wind speeds above 8m/s the two curves follow well each other with the design curve being higher than phase3. The lack of high westerly winds during the autumn of 1995 and the whole year of 1996 has hindered the completion of the power curve of this phase.

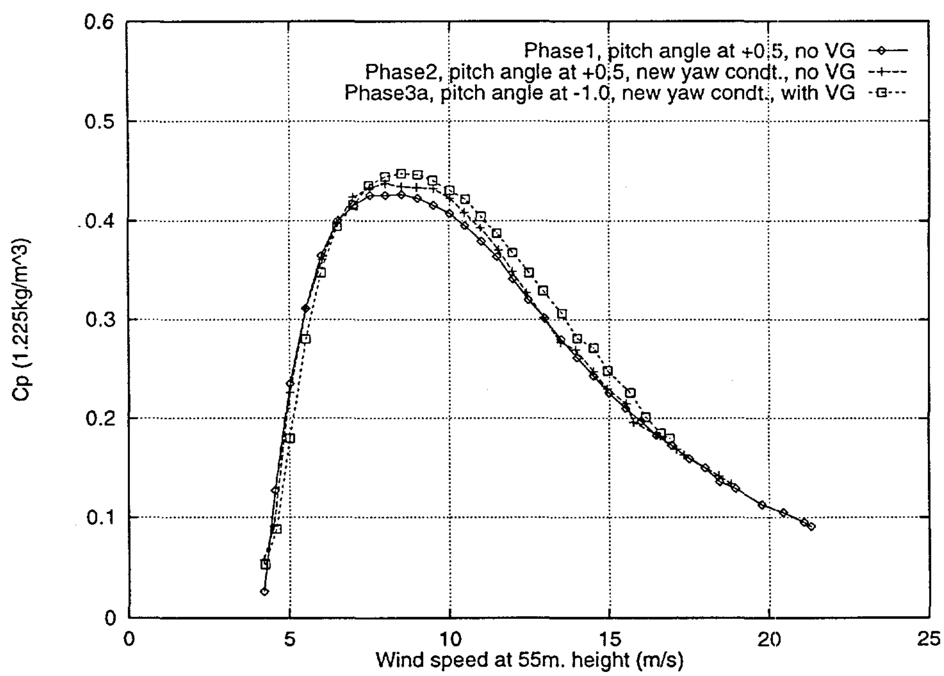

Figure 6-3 The power coefficients for the three phases

The power coefficients C_p for the three phases are shown in Figure 6-3. Below 7m/s the phase3 curve lies lower, while at higher wind speeds it reaches higher values than the two others. In line with the above results from the power curves, it is seen that the phase2 curve is above the phase1 curve between 7m/s and 12m/s.

6.2 *Relation between the mast- and the non-corrected nacelle anemometer power curves (nacelle anemometer at 1.2m. or 3m. height)*

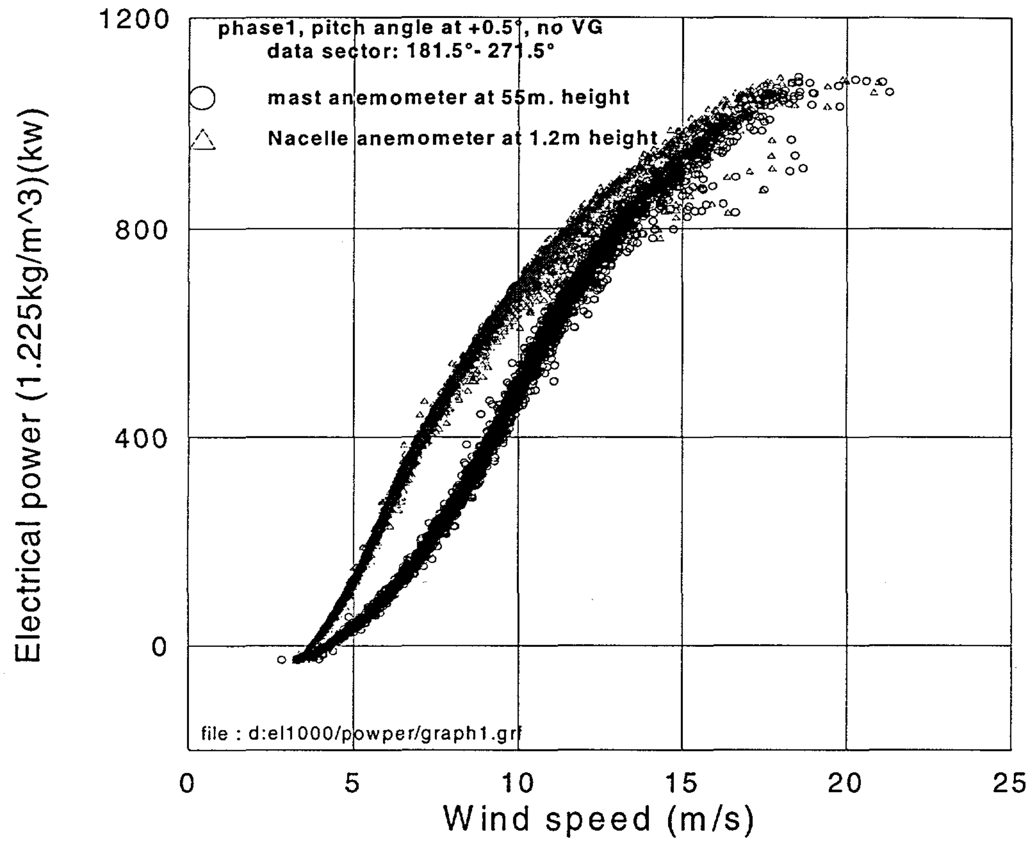

Figure 6-4 Phase1, the power curve as a function of the mast and the non-corrected nacelle anemometer. The distance between the two power curves is minimized at low and high wind speeds

In Figure 6-4, the power curves for the phase1 data are shown both for the mast and the nacelle anemometer (not corrected, placed 1.2m above the nacelle and behind the non-profiled part of the blade). The difference (distance) between the two power curves, in other words the deficit of the wind speed recorded by the nacelle anemometer relative to the mast anemometer, is minimized for very low and very high wind speeds, where extraction of energy from the wind is minimum according to Figure 6-3, while it reaches a maximum at values around the maximum C_p. Therefore it may be argued that there is a direct relation between the curves in Figure 6-3 and Figure 6-4, as increased power extraction from the incoming wind results in higher retardation of the air coming through the turbine's rotor. This is illustrated in Figure 6-4 where, for wind speeds around max. C_p, the nacelle anemometer records a much lower wind speed as compared to the mast anemometer. This is also an indication that the relation between the two cup anemometers is not as a rule linear.

In Figure 6-5 the power curve from phase3a is presented as a function of the nacelle and the mast anemometer with the nacelle anemometer at 1.2m height from the roof and behind the non-profiled part of the rotor. When comparing Figure 6-4 and Figure 6-5, the gap between the corresponding power curves is seen to be more narrow for the phase3a data. The two power curves approach again each other at higher wind speeds but the rate in the case of phase3a data is lower and the two curves have a tendency to run almost parallel with each other. Thus the relation between the nacelle and the mast anemometer is now different when compared to Figure 6-4. The presence of the vortex generators, the modification of the yaw, and the modification of the pitch angle has influenced the flow field around the rotor and the relation between the mast and the nacelle anemometer.

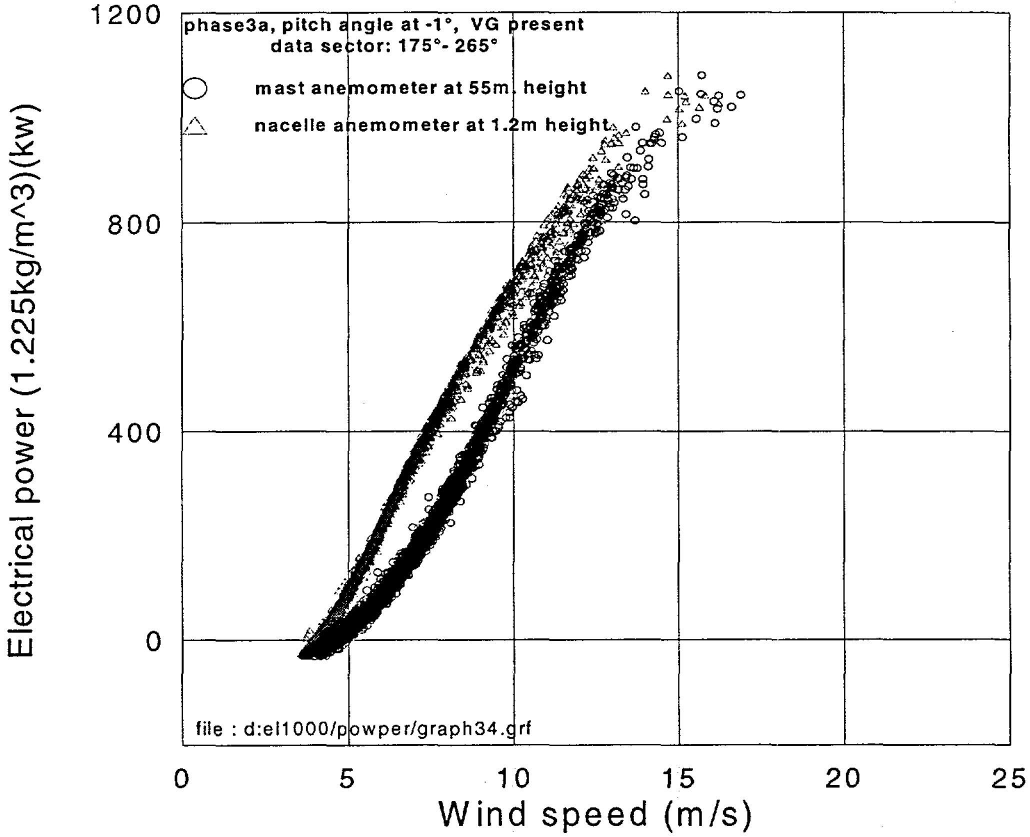

Figure 6-5 Phase3a, the power curve as a function of the mast and the non-corrected nacelle anemometer. The nacelle anemometer is placed behind the non-profiled part of the rotor. The distance between the two power curves is minimized at low and high wind speeds however the tendency at higher wind speeds is different when compared to Figure 6-4.

In Figure 6-6, the relation between the nacelle and the mast anemometer is presented for the phase3b data when the nacelle anemometer is at 3m. height above the roof and behind the profiled part of the blade. Before proceeding with the analysis of the figure it should be mentioned that the data points which deviate from the main body of the power curves respond to an icing situation which occurred during the measurement period. The two power curves are again close to each other at low wind speeds while at higher speeds, contrary to the previous results, the deficit in wind speed as recorded by the nacelle anemometer remain almost constant, also beyond stall. By comparing Figure 6-5 and Figure 6-6 it is seen that the wind speed recorded by the nacelle anemometer in phase3b at 3m height is lower compared to the phase3a data recorded at 1.2m height. The higher retardation is probably a result of the larger amount of energy extracted by the profiled part of the blades in front of the anemometer. This conclusion is however different than the one reached after analyzing Figure 6-3 and Figure 6-4 as here the behavior of the flow recorded by the nacelle anemometer seems to be influenced more by the flow condition of the blade segment in front. The extraction of any further conclusions is nevertheless hindered by the lack of knowledge of the behavior of the surface flow in the presence of VG.

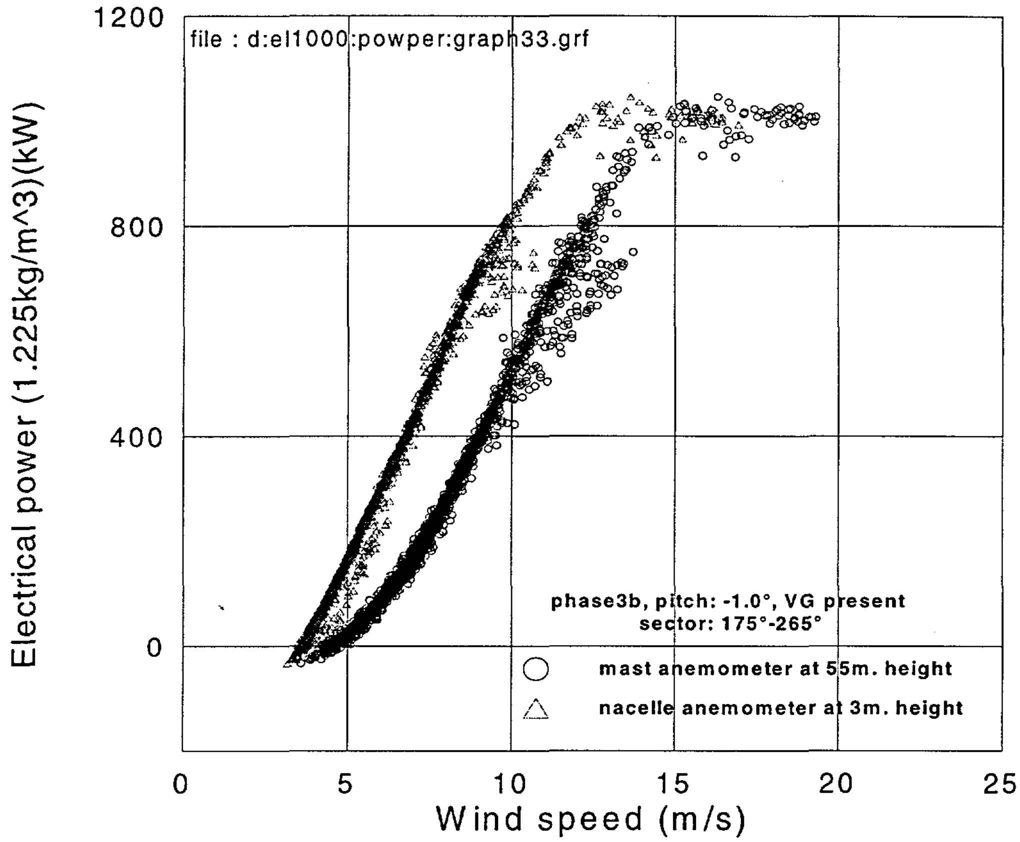

Figure 6-6 Phase3b, the power curve as a function of the mast and the non-corrected nacelle anemometer. The nacelle anemometer is placed behind the profiled part of the rotor

In Figure 6-7 an example (taken from Ref. 9) of the surface flow patterns on a blade at different wind speeds is presented According to Figure 6-7 the calculated separation pattern on an LM19.1 blade appears at the hub of the blade and near the trailing edge and develops as the wind speed becomes higher towards the tip and the leading edge of the blade. The presence of VG will delay this process and will allow the flow to stay attached up to higher wind speeds. Thus if a corresponding behavior is assumed for the blades of ELKRAFT turbine, it is natural to expect that the air flow in the neighborhood of the nacelle anemometer does get more retarded in the case of the phase3a data relative to the case of the phase1 data since the presence of the vortex generators keep the flow attached on the blade surface resulting in that more energy is extracted from the flow.

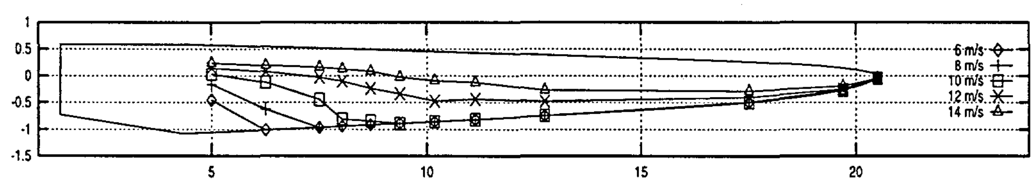

Figure 6-7 Separation pattern for an LM19.1 blade mounted on a Bonus M41(XFOIL calculations), (from Ref. 9). The separation of the surface flow appears at the hub of the blade and develops towards the tip and the leading edge.

This is in accordance with the results presented in Figure 6-8 where a direct comparison of the bin power curves as a function of the non-corrected nacelle anemometer at 1.2m height and for two rotor conditions is presented. It is evident that the non-corrected nacelle anemometer cannot be used for a comparison of the power curves of a turbine after rotor modifications have taken place. In fact in the figure, the phase3a power curve lies well below the phase1 curve up to 10m/s which should lead to the wrong conclusion that the modifications had a negative effect.

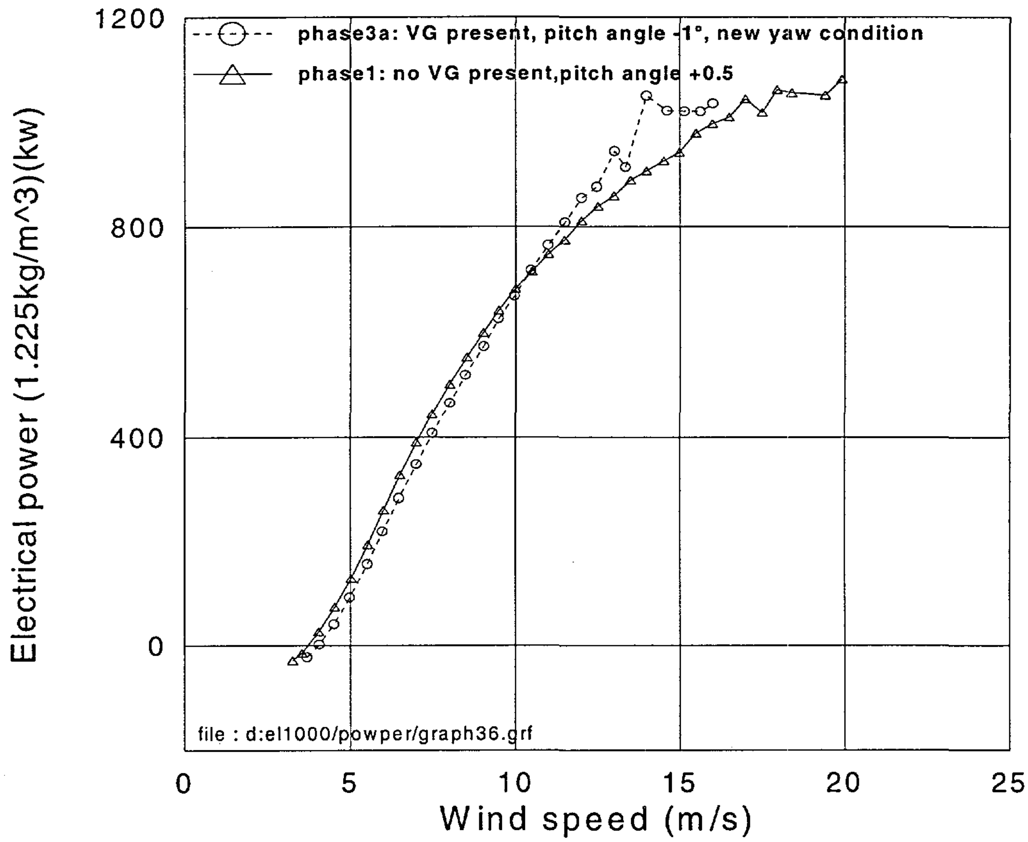

Figure 6-8 The power curve as a function of the nacelle anemometer at 1.2m height above the roof

The main conclusions from the above results is that the relation between the mast and the nacelle anemometer depends both on the position of the nacelle anemometer and the characteristics of the rotor. The relation changes as soon as one or both of these factors are modified. Therefore it seems to be of less importance where the cup anemometer is placed on the nacelle as long as the relation between the mast and the nacelle anemometer is determined. The non corrected nacelle anemometer cannot be used to draw any conclusions concerning the turbine's power curve once modifications have taken place.

6.3 *Relation between the mast and the nacelle anemometer (turbine in operation)*

In Figure 6-9, the relation between the mast and the nacelle anemometer is shown with the help of raw data from phase1, their bin values and a polynomial curve fitted on the bin values. The relation is not linear and the points have in this case been approximated by a 5th order polynomial curve. When trying to establish the relation between the nacelle and the mast anemometer it is a common practice that the sector used around the mast-turbine direction should be as narrow as possible (e.g. +- 20°). In the present case, since the terrain in the sector used is flat and homogeneous (water), a wider sector has been used due to the lack of high wind speeds within a more narrow sector. This however has not taken place at the cost of the accuracy of the correlation at low speeds as can be verified from the

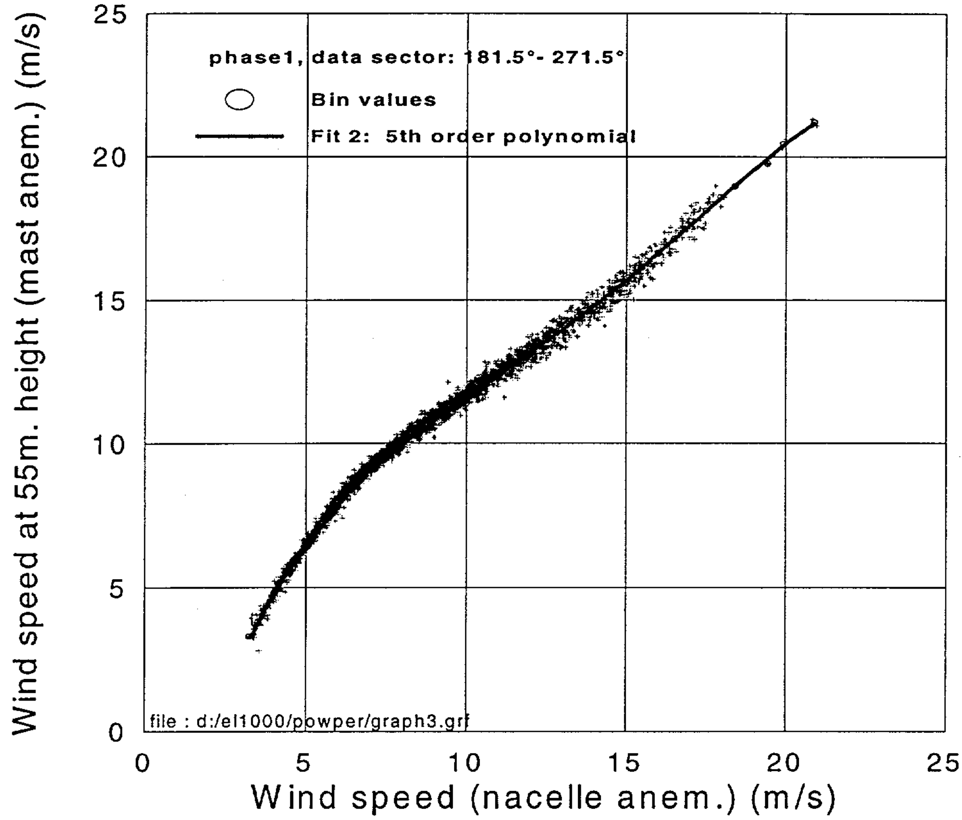

Figure 6-9 Relation between the nacelle and the mast anemometers for the phase1 data. Data fitted a 5th deg. polynomial

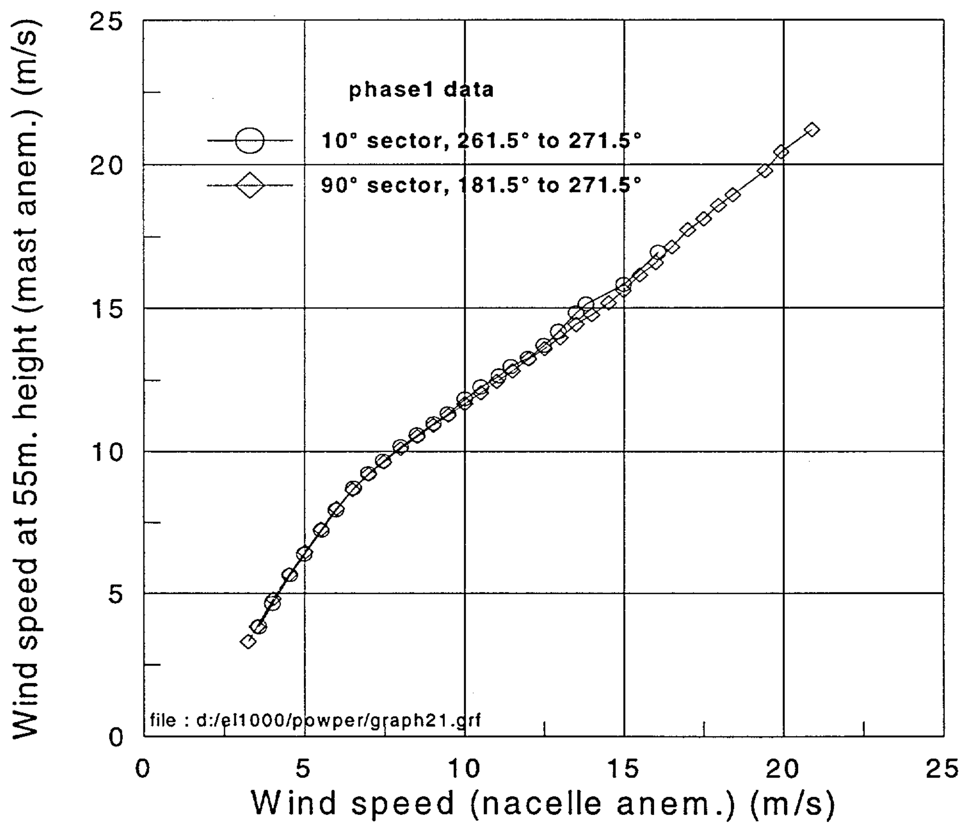

Figure 6-10 Relation between the mast and the nacelle anemometer for the phase1 data and for two different wide sectors

following Figure 6-10, where the bin data are presented for two different sectors (10° and 90° wide). The agreement is good at lower wind speeds but becomes poorer at higher wind speeds due to the lack of an adequate number of data points in the narrow sector.

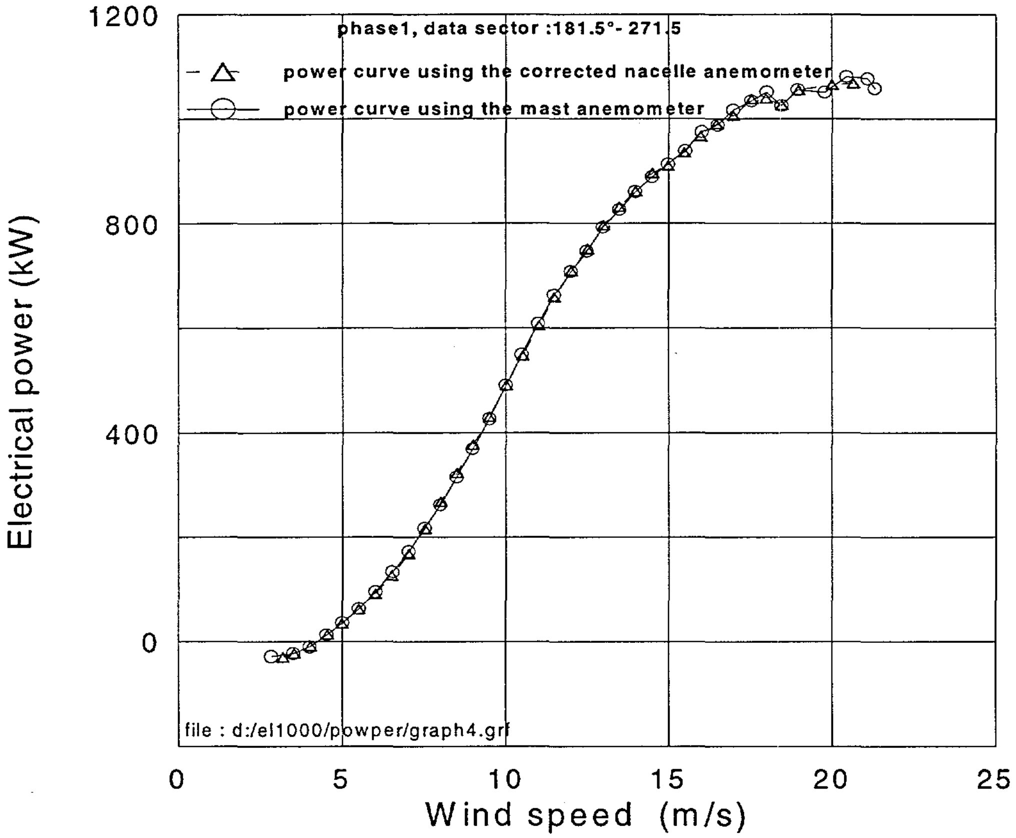

Figure 6-11 The bin averaged power curve for the phase1 data as a function of the mast and the corrected nacelle anemometer. The two curves practically coincide

In Figure 6-11 the reproduction of the power curve as a function of the corrected nacelle anemometer (via the 5th degree polynomial) for the case of the phase1 data is shown together with the mast power curve (bin values). The data are from the sector 181.5° to 271.5°. The two power curves are as expected practically identical. This means that, once the relation between the mast and the nacelle anemometer is established, it is possible to use the nacelle anemometer instead of the mast anemometer and correctly describe the turbine's power curve. Similar relations as the one shown in Figure 6-11 can be established for all the data sets for the different measurement phases

As already mentioned above, the mast-nacelle relation depends on a number of factors and for the present case the best fit has been a 5th deg. polynomial. Following this fit there is nothing surprising in the fact that the two power curves in Figure 6-11 coincide. The reason for presenting the good agreement bet. the two curves is in order to underline that correct approximation leads to exact representation of the power curve which is not the case in the results shown in Ref. [3] to [4]. In the case of Ref. [2] the slope is linear and less than unity which indicates an acceleration of the flow behind the rotor. The nacelle anemometers both in the present case and in Ref. [2] have been mounted following the instructions given in Ref. [1]. This along with the above results indicates that the mounting procedure described in Ref. [1] does not result in a universal relation between the mast and the nacelle anemometer as the relation depends mainly on the qualities of the rotor. In Ref. [3] the shape of the line of the bin data values is similar to the curved shape seen in the Figure 6-9. Despite this, the authors have chosen to approximate the relation as a straight line which by the way has a slope higher than unity, indicating retardation of the flow. In the same reference it can be seen that the straight line approximation has resulted in discrepancies between the two power curves plotted as a function of the mast and the (corrected) nacelle anemometer. In the case of Ref. [4] only the mast and the corrected nacelle anemometer power curves are presented but also here it is evident that the authors have chosen a simpler form for the approximation of the mast-nacelle anemometer relation and as a result differences exist between the two power curves. Both in Ref. [3] and Ref. [4] however it can be seen that these approximations do not result in systematic differences in the power curves (i.e. the power curves cross each other) and as a result when the AEP is calculated the differences cancel out up to a certain degree. Therefore the simplified approximation of the mast-nacelle relation affects mainly the power curve shape and to a lesser degree the AEP calculation.

6.4 *Relation between the mast and the nacelle anemometer (turbine stopped)*

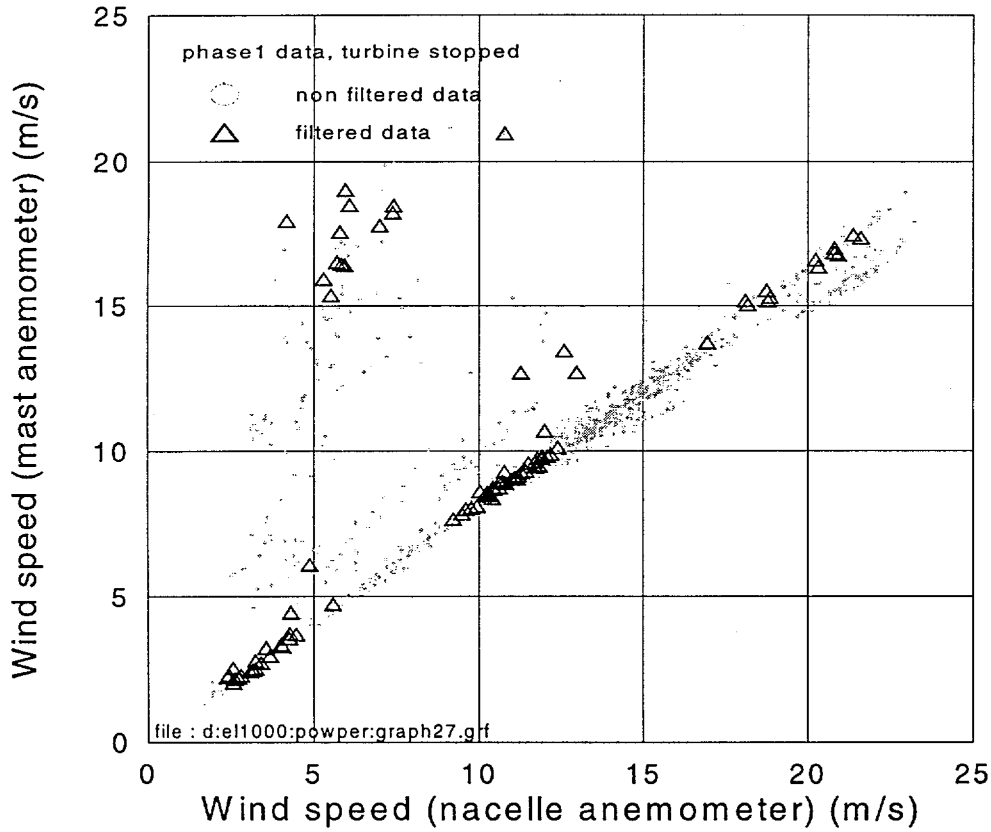

Figure 6-12 Relation between the mast and the nacelle anemometer at 1.2m height with the turbine stopped

Next the relation between the mast and the nacelle anemometer is presented when the turbine is stopped. WA^{S}P calculations, not presented here, have confirmed the absence of any site effects within the sector 181.5° to 271.5° and therefore any influence is due to the presence of the nacelle. The way the nacelle presence influences the cup anemometer is really of not great importance as it is by "default" included in the relation derived when the turbine is in operation.

The relation is presented in Figure 6-12 and Figure 6-13. In the case of Figure 6-12, the data have been filtered with respect to the position of the blades and the yaw error of the turbine. Thus the stopped turbine is oriented towards the mast and one of the blades is always oriented around the vertical and downwards With the exception of a few data points, the relation between the two anemometers is linear and the flow above the nacelle at the anemometer position is accelerated. In Figure 6-13 the raw data for the two heights of the nacelle anemometer are shown. It is interesting to observe that in this case the acceleration of the flow at 3m height is higher relative to the 1.2m. The acceleration of the flow explains why the relation of the nacelle to the mast anemometer is sometimes, as e.g. in the case of Ref.[2], larger than unity.

As the presence of the nacelle is seen to influence the response of the anemometer, it can be argued that the relation mast-nacelle anemometer is influenced also by the shape of the nacelle and therefore the relation derived for specific rotor settings and a specific nacelle is not necessarily valid for the same rotor settings and a different nacelle shape.

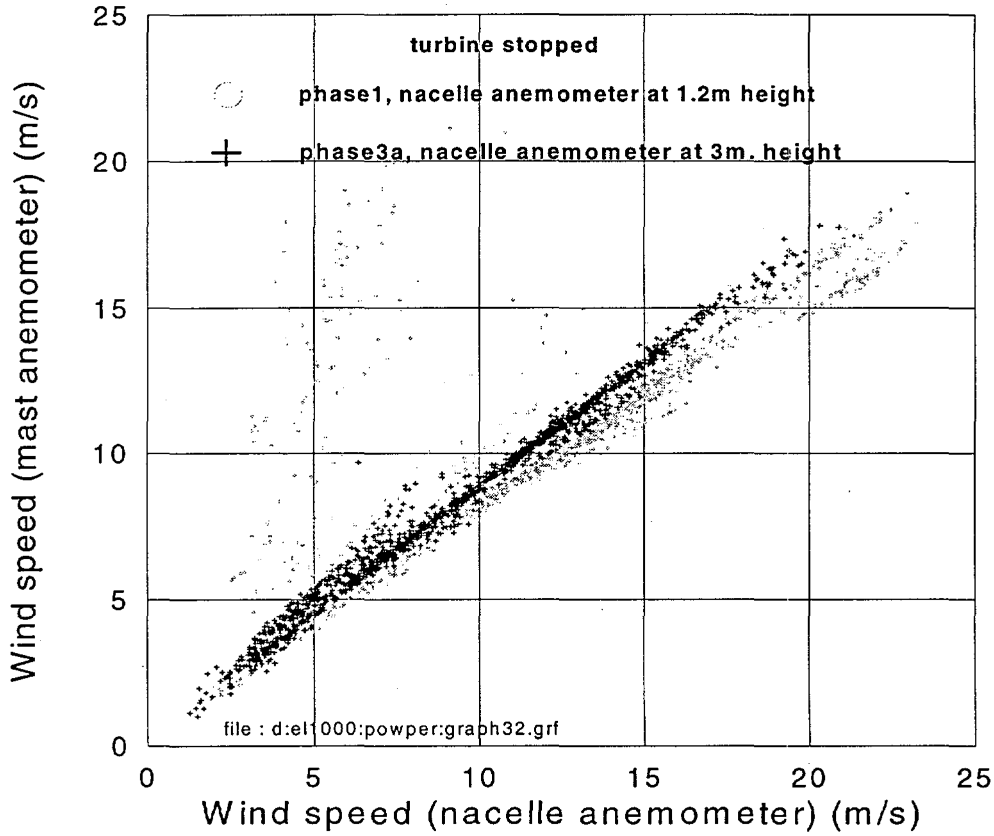

Figure 6-13 Relation between the mast and the nacelle anemometer at 1.2m and 3m height, turbine stopped

6.5 *The power curve as a function of the corrected nacelle anemometer (same rotor settings - different sectors)*

The conclusion from the above chapters is that once the relation between the nacelle and the mast anemometer is established, then the nacelle anemometer can be used for the verification of the turbine's power curve within the same sector. When using the same sector then by default the same data are used for the power curve as a function of the mast or the corrected nacelle anemometer and therefore the result may be considered as biased. An extension of the above work is to show whether and under which conditions the relation between the nacelle and the mast anemometer is valid for different data sets and for different sectors. For that purpose the turbine's bin power curves from the sector 181.5° to 271.5° (phase1 data) or 165° to 275°(phase3a data) will be compared to the bin power curves derived as a function of the "corrected" nacelle anemometer from other sectors. The sectors used are shown in the following table together with a sort description of the terrain roughness within the sector.

Sector	Terrain description
181.5°→271.5°	Fetch above land and sea
271.5°→330°	Fetch above land, from 4D to 13D dominated by the power plant, coal banks, oil tanks and cinder deposits
330°→360°	Fetch above land, urban conditions
0°→90°	Fetch above land and sea
100°→180°	Fetch above land and sea

Table 6-1 A description of the terrain within the sectors used

In Figure 6-14, the power curve from the sector 181.5° to 271.5° is given as a function of the mast anemometer and it is compared to the power curve from the sector 100° to 180°which is presented as a function of the corrected nacelle anemometer. The surface roughness is the same for the two sectors and the power curves are identical, the minor differences at higher wind speeds being attributed to the limited number of data points in the corresponding bins

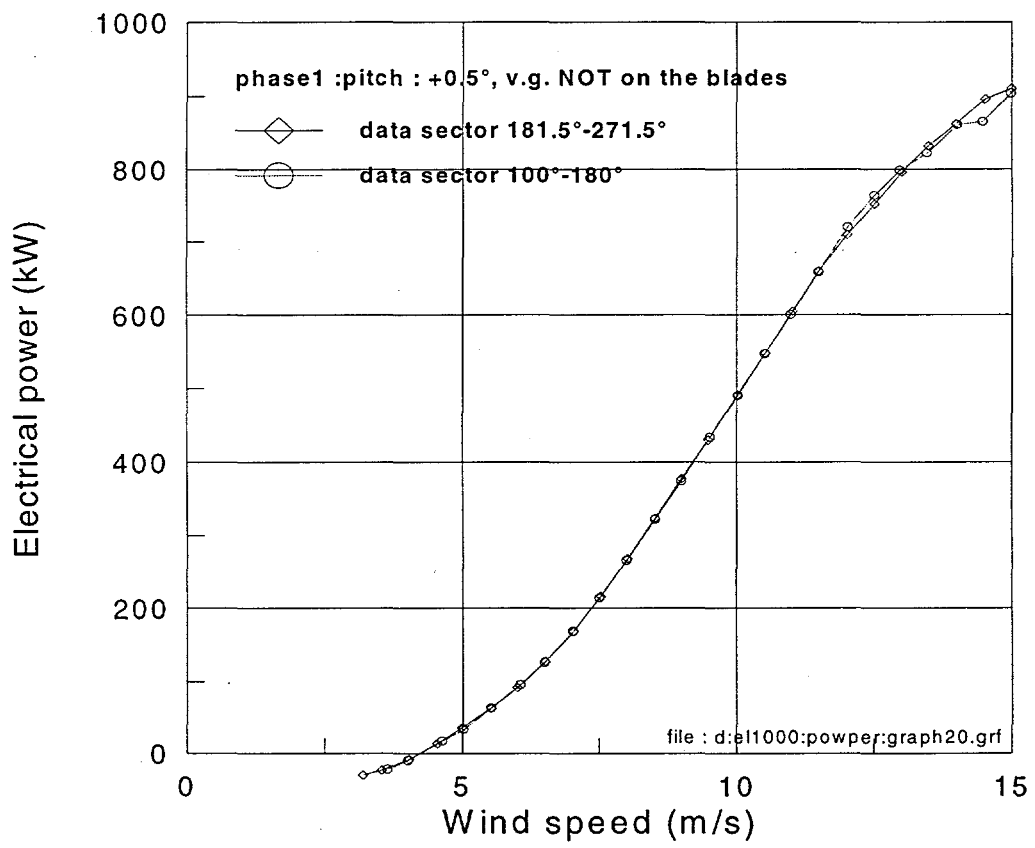

Figure 6-14 The power curve for two different sectors as a function of the mast and the corrected nacelle anemometer

The same good agreement is observed in the case the phase3a data shown in Figure 6-15 where the power curve from the sector 175° to 265° is given as a function of the mast anemometer and it is compared to the power curve from three other sectors which are presented as a function of the corrected nacelle anemometer. It is only the sector 330° to 360° which has a bigger surface roughness compared to the rest. For this sector theoretical calculations, not presented here, show that minor differences to the design power curve should be observed at around the nominal power.

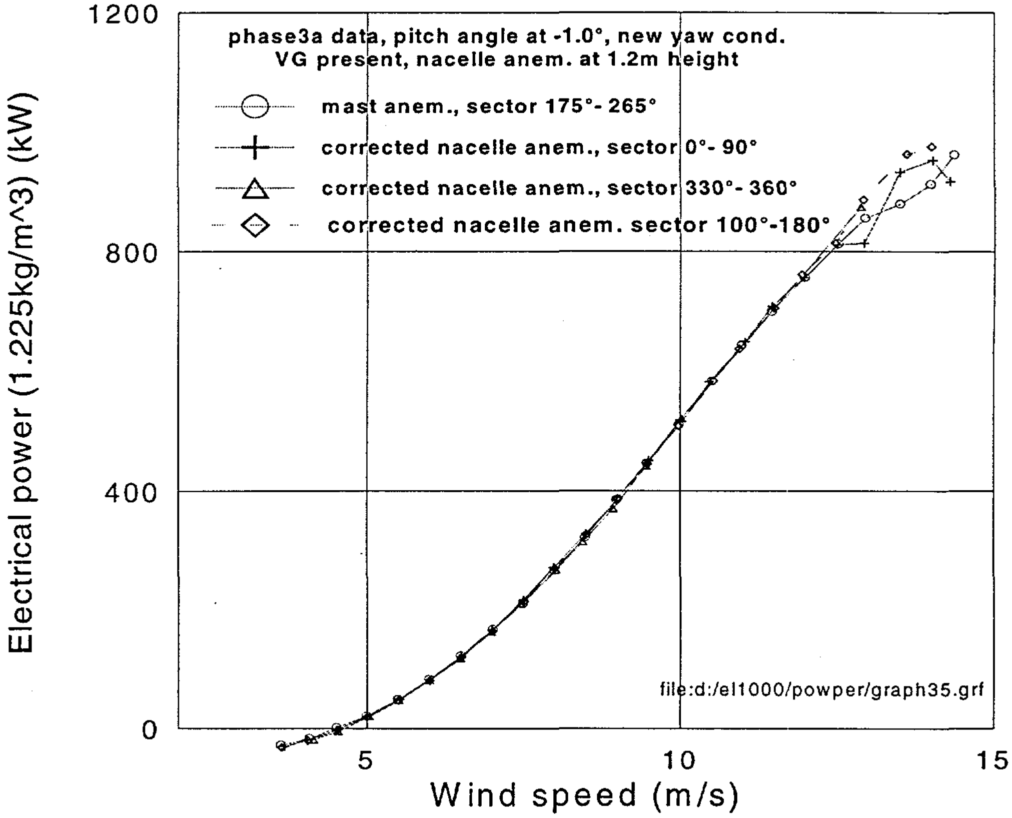

Figure 6-15 The power curve for four different sectors as a function of the mast and the corrected nacelle anemometer

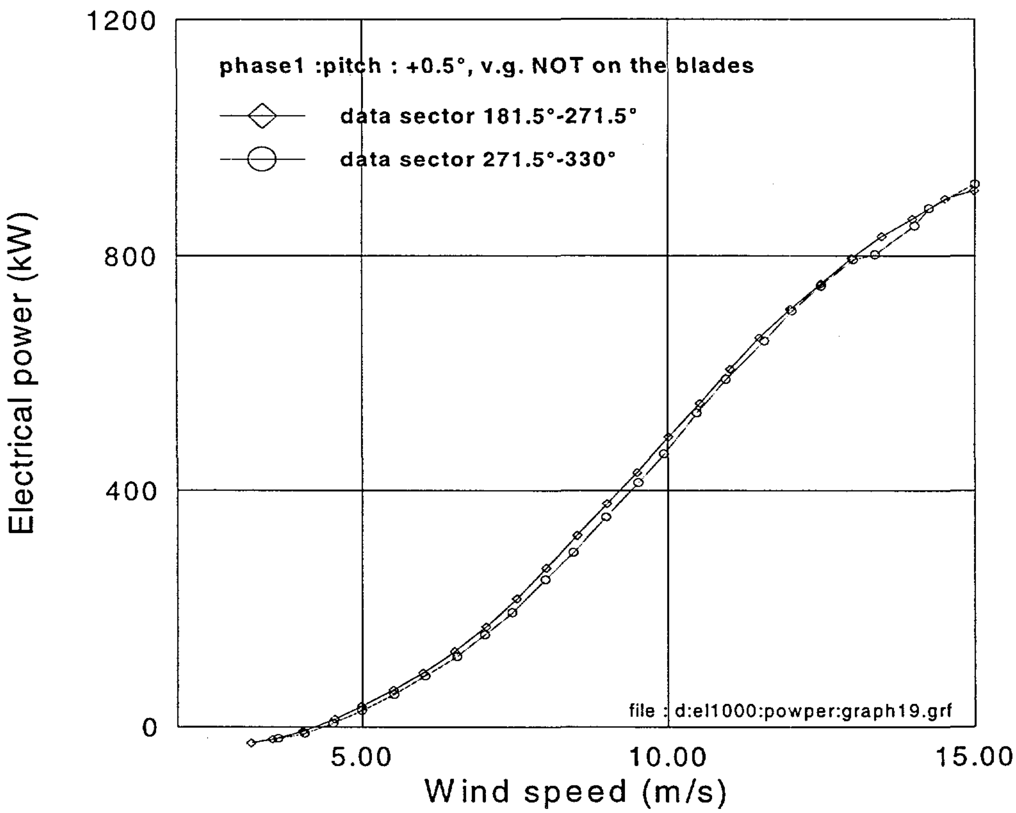

Figure 6-16 The power curve for two different sectors as a function of the mast and the corrected nacelle anemometer

Finally in Figure 6-16, the power curve as a function of the mast anemometer from the sector 181.5° to 271.5° is compared to the power curve as a function of the corrected nacelle anemometer from the sector 271.5° to 330°. The last one is the sector where the turbine operates in the wake of the power plant and the coal bunks as these can be seen in Figure 3-4. Unlike the previous cases, the two power curves do not coincide with the one from the sector 271.5° to 330° laying systematically below.

The reason for the lack of coincidence is seen in Figure 6-17 where the 5[th] order polynomial line fitted to the results from the sector 181.5° to 271.5° is presented together with raw data from the sector 271.5° to 330°. The correlation mast-nacelle anemometer is poor compared to the data of the sector 181.5° to 271.5° (Figure 6-9). This is expected since the mast anemometer is not within the 271.5° to 330° sector and it therefore "sees" another part of the complex terrain in front, compare to the nacelle anemometer. That the relation depends strongly on the wind direction is shown in Figure 6-17 as considerable level differences in the measured wind speeds. As a result it is concluded that the presence of the obstacles which generates another terrain type modifies the wind speed profile relative to the flat terrain measurement sector and thereby modifies the relation between the mast and the nacelle anemometer.

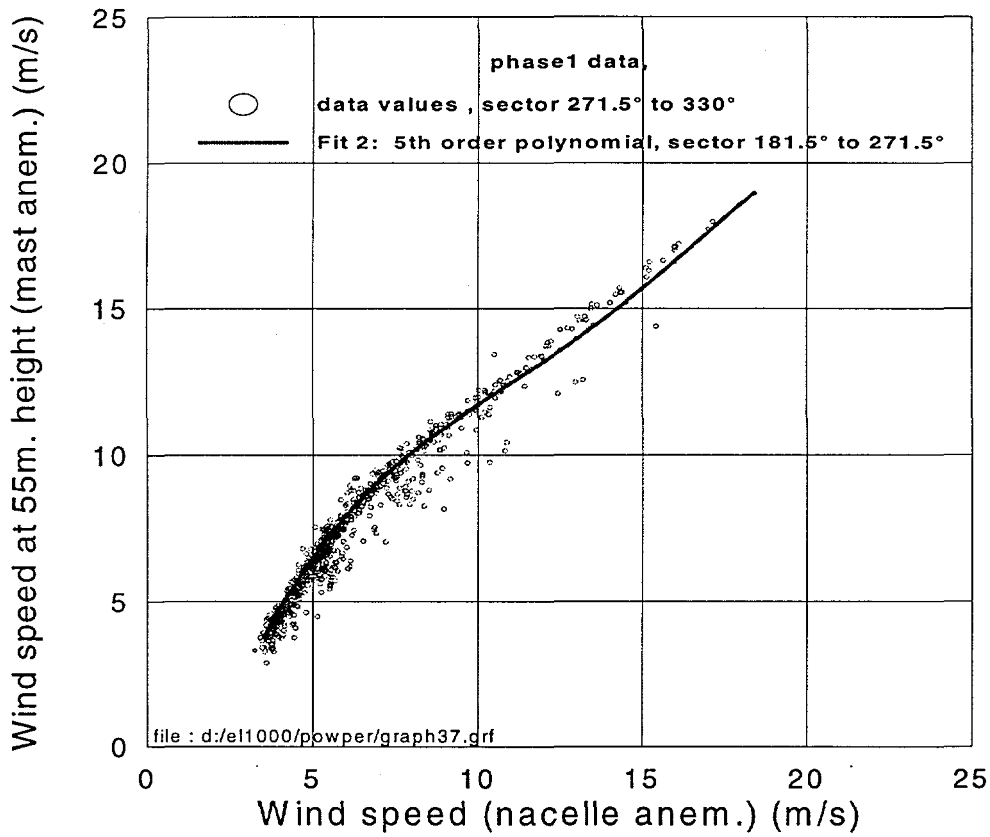

Figure 6-17 Comparison between the nacelle and the mast anemometer for the phase1 data and for two different sectors

The wind shear through the rotor plane and for the two sectors, here defined as the difference in the speed registered by the cup anemometers at 75m and 35m, is presented as a function of the anemometer at hub height (55m) in Figure 6-18. The slope is seen to be bigger in the case of the 271.5° to 330° sector. This means that, within the rotor area, the speed deficit of the wind profile, with descending height, is higher in the case of the sector 271.5° to 330° compared to the sector 181.5° to 271.5°. The flow within this sector resembles the flow behind a fence where the wind speed suffers a deficit when compared to the inlet profile. A result of this deficit is the reason for the lower energy produced by the turbine. We examine now how much this difference in the power curves means to the annual energy production (AEP) of the turbine.

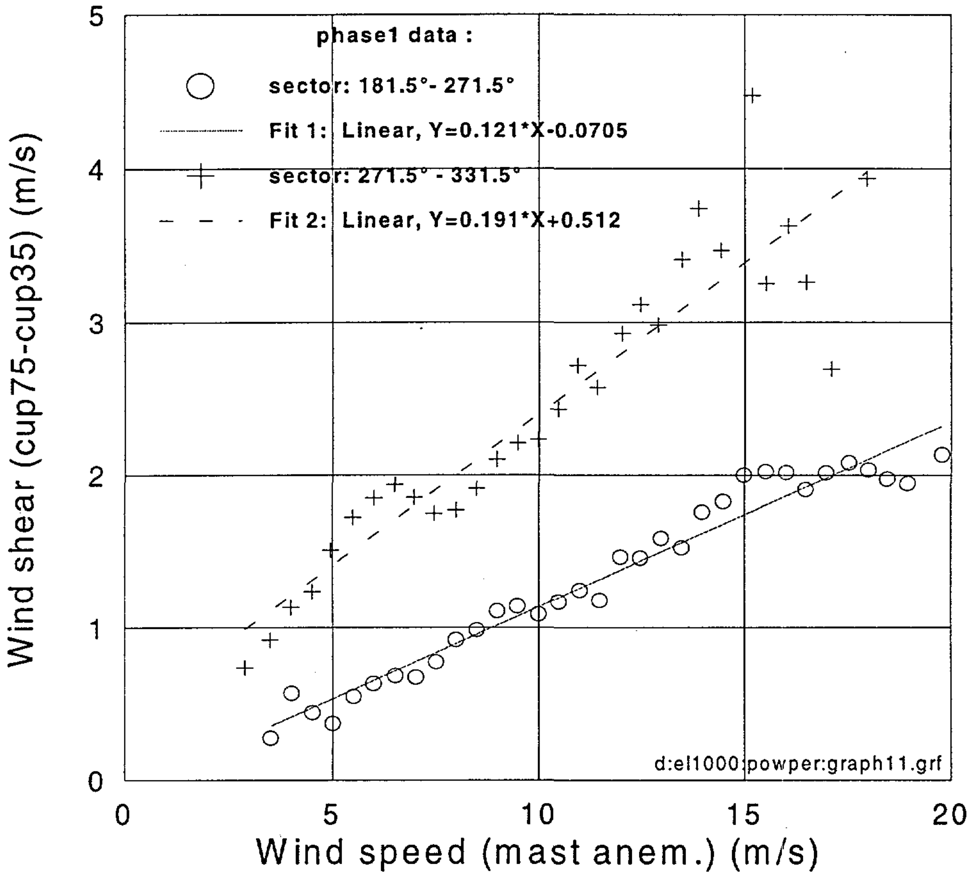

Figure 6-18 The wind shear for the two sectors (phase1 data)

The AEP and the related uncertainties, calculated according to Ref. [6], for the two power curves are shown in the following Table 6-2 (power curve as a function of the mast anemometer) and Table 6-3 (power curve as a function of the corrected nacelle anemometer). The same sources of uncertainty have been considered for both power curves except for the case a form factor of two Table 6-3. There the second uncertainty column is calculated with an additional 1% calibration uncertainty. The mean AEP values, shown in Table 6-3, agree with the mean AEP values shown in Table 6-2 within the stated uncertainties however the deviations are large.

AEP-measured and related uncertainty[MWh], sector 181.5° to 271.5°										
Wind speed	Form factor									
	1.50		1.75		2.00		2.25		2.50	
4	607.8	82.8	497.6	80.1	414.0	77.0	350.8	74.0	302.6	71.4
5	1120.4	106.0	997.8	107.1	893.5	106.8	808.0	105.6	738.6	104.1
6	1690.8	124.4	1594.5	129.9	1497.6	133.5	1410.8	135.7	1335.6	136.9
7	2254.9	137.3	2222.4	146.5	2160.8	153.6	2094.9	159.2	2032.7	163.6
8	2766.2	145.4	2827.4	157.3	2827.0	166.9	2800.9	174.9	2767.2	181.7
9	3197.9	149.5	3368.4	163.0	3451.5	174.3	3483.1	183.8	3489.9	191.9
10	3540.3	150.7	3819.0	164.9	3998.4	177.0	4104.7	187.2	4165.0	196.0
11	3795.7	149.7	4168.4	163.8	4443.5	176.0	4634.7	186.4	4762.1	195.3

Table 6-2 The annual energy production, power curve vs. the mast anemometer, phase1 data

AEP-measured and related uncertainty [MWh], sector 271.5° to 330°											
Wind speed	Form factor										
	1.5		1.75		2			2.25		2.5	
4	567.8	80.7	457.3	77.6	374.2	74.1	76.3	312.0	70.8	265.0	68.0
5	1065.9	103.7	940.3	104.7	833.4	104.0	108.2	746.1	102.4	675.6	100.4
6	1624.4	121.4	1524.8	127.5	1423.7	131.2	137.5	1332.6	133.2	1253.8	134.0
7	2177.4	133.0	2142.9	143.4	2078.0	151.4	159.3	2007.7	157.5	1940.6	161.9
8	2677.9	139.3	2738.1	152.4	2736.7	163.5	172.5	2708.5	172.9	2671.2	180.6
9	3099.3	141.7	3268.4	155.9	3352.2	168.6	178.1	3384.6	179.8	3391.3	189.6
10	3432.7	141.1	3708.2	155.5	3888.2	168.4	178.1	3997.0	180.1	4060.2	190.6
11	3680.5	138.6	4047.6	152.3	4321.5	164.6	174.1	4514.8	175.7	4646.3	185.8

Table 6-3 The annual energy production, power curve vs. the corrected nacelle anemometer, phase1 data

These discrepancies in the power curves and the AEP, shown in Figure 6-16 and the above tables would certainly be smoothed out if a wider sector was chosen and it would thus be wrongly argued that the nacelle-mast relation is still well applicable. Therefore if the verification of a power curve is wanted and the relation of the mast-nacelle anemometer is known care should be taken to apply this relation in mutually alike sectors.

The presence of the obstacles in the sector 271.5° to 330° simulates in many ways complex terrain conditions for the turbine and the conclusion is that the relation between the mast and the nacelle anemometer derived at one location and under the influence of specific site conditions is not transferable at another location where different conditions prevail. The task of transferring the relation between different terrain types is however not easy as procedures on this subject are not yet agreed. The second important conclusion from Figure 6-18 is that since the turbine's power curve depends on the shape of the wind profile, then in the presence of site effects the correct relation between the two anemometers at a hub height is necessary but may be not sufficient for the description of the power curve under complex terrain conditions as it does not give any information on the wind profile shape.

6.6 *The power curve as a function of the corrected nacelle anemometer: (different rotor settings - same sector)*

We now proceed to examine the effect of the changes of the rotor settings on the relation between the nacelle and the mast anemometer for the three phases of the measurement program, for the same position of the nacelle anemometer and for the same sector. Following this we will apply two different nacelle-mast anemometer relations corresponding to two different rotor settings on the same data set.

The results of the relation nacelle-mast anemometer are shown in Figure 6-19. By comparing the curves from the first and the second measurement phase differences are observed. This means that the relation between the mast and the nacelle anemometer depends not only on the rotor settings but also on the yaw settings of the turbine. Once the settings have changed a new relation should be established. The differences become even more pronounced between the phase1 and the phase3a data. We proceed now to investigate to what extent these differences can affect the power curve presentation and the AEP since this cannot be estimated from the figure.

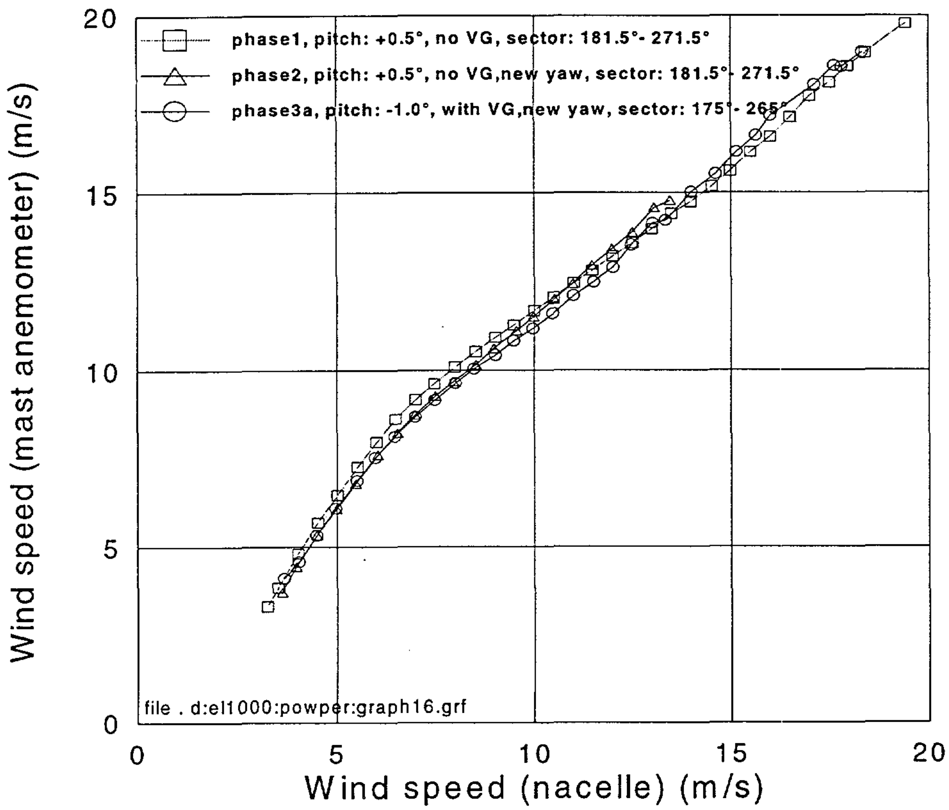

Figure 6-19 Relation between the nacelle and the mast anemometer for three different rotor settings

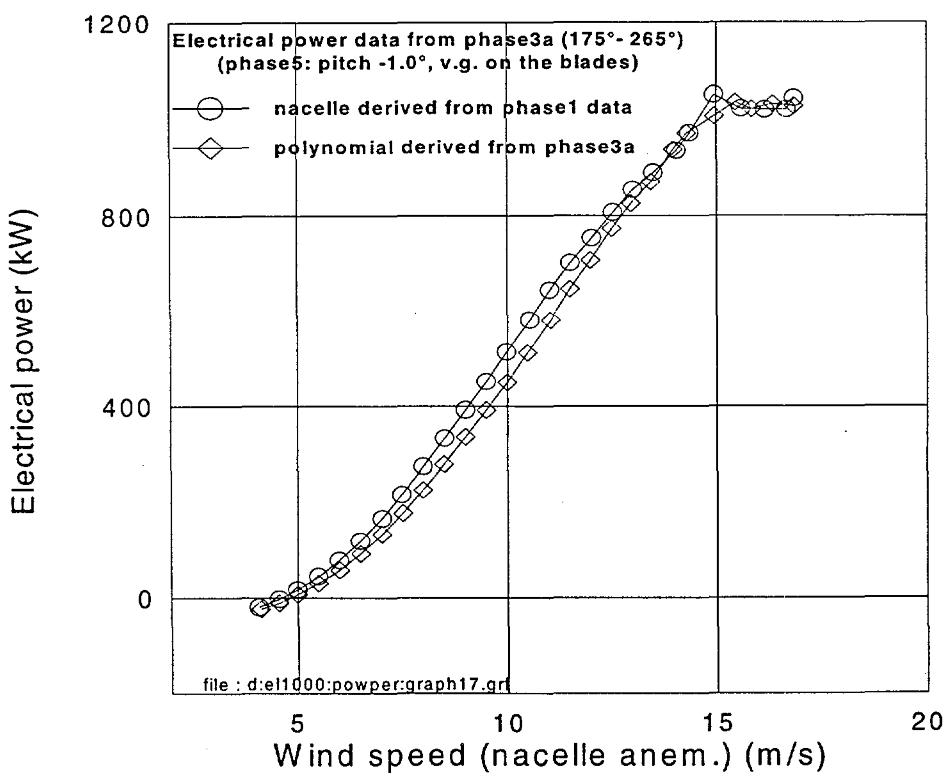

Figure 6-20 The power curve of the turbine when using different corrections for the nacelle anemometer (the stall points are not confirmed by later results)

In Figure 6-20 the power curve from the phase3a data is presented as a function of the corrected nacelle anemometer using both the relation derived during the phase1 (wrong) and the phase3a (correct) measurements.

The use of the wrong relation produces a wrong power curve which in this case is overestimated but the opposite might as well be true. The most important observation is that the differences between the two power curves are in this case systematic, which means that a bias error will be introduced in the AEP calculations which cannot be in any way detected. Therefore if a derived relation, between the mast and the nacelle anemometer in one turbine, should be used in another turbine of the same type and make , care should be taken that the rotor settings, the yaw error and the placement of the nacelle anemometer remain unchanged.

7. Conclusions

The use of the nacelle anemometer as an alternative to the use of a free mast anemometer for verification of power performance measurements has been investigated, using measurement results from the ELKRAFT 1MW wind turbine.

The power curve in stall regulation mode was measured in the following phases:

1 pitch 0.5°, nacelle anemometer height 1.2m (in blade cylinder wake region), high yaw error

2 pitch 0.5°, nacelle anemometer height 1.2m (in blade cylinder wake region), low yaw error

3a pitch -1.0°, nacelle anemometer height 1.2m (in blade cylinder wake region), low yaw error and vortex generators on blade

3b pitch -1.0°, nacelle anemometer height 3.0m (in profiled blade wake region), low yaw error and vortex generators on blade

The power curves measured with the mast anemometer show an improvement in the wind speed range 7-12m/s when having low yaw error compared to high yaw error (phase 1 and 2). Phase 3 measurements show a substantial improvement of the power curve due to the new pitch setting and the presence of the vortex generators compared to phase 1 and 2, and the power curve is very close to the design power curve.

The power curves measured as a function of the nacelle anemometer were compared with the power curves measured as a function of the mast anemometer for the same wind turbine settings. It was found generally, that with the nacelle anemometer in the blade cylinder wake region there was very high wind speed deficit in the max. Cp region, whereas this deficit was reduced at low and high wind speeds. With the nacelle anemometer in the profiled blade wake region the wind speed deficit seemed much more constant for medium to high wind speeds. Thus the response of the nacelle anemometer is a function of its location on top of the nacelle. From the comparison it can also be concluded that the modifications on the wind turbine rotor settings, which results in changes of the power curves seen as a function of the mast anemometer, does also change the power curves seen as a function of the nacelle anemometer, but not in a consistent way. This is due to the three dimensional nature of the flow through the rotor and the fact that the wind speed registered by the cup anemometer is of local nature and only representative of that measurement point. In other words, it was found that the nacelle anemometer power curves cannot be used to draw any conclusions concerning the changes of the power curve of the wind turbine due to the modifications made. The main conclusions is thus, that the power curves, using the nacelle anemometer, are dependent on both the position of the nacelle anemometer on the nacelle and the characteristics of the rotor.

The relations between the mast anemometer and the nacelle anemometer were not linear in this study, but they could be fitted well with a 5^{th} order polynomial curve in the case where the cup anemometer is behind the non profiled part of the blade. Behind the profiled part this relation changes.

For the same wind turbine settings a very good agreement was found between the measured power curve (phase 1 data) measured from an open sea sector 181.5° to 271.5° and a power curve, derived from combining the relation between the mast and nacelle anemometers and the measured power curve using the nacelle anemometer with data from same sector. The same very good agreement was found when combing the relation between the mast and nacelle anemometers and measured power curves from another open sea sector (100° to 180°). The same very good agreement was also found with power curve data from phase 3a (175° to 265°) when combining the relation between the mast and nacelle anemometers and measured power curves from other sectors: a mix of sea and flat land 0°

to 90° (low roughness) and an industrial area 330° to 360° (high roughness). On this basis it can be concluded that the nacelle anemometer can be used to verify the same power curve with winds from different terrain roughness'. It was not possible, though, to find good agreement when using wind data (phase 1) from the sector in the wake of a huge power plant (271.5° to 330°). The cause of this is found to be due to the disturbed wind profile which results from the presence of site effects.

For the same measurement sector (about 180° to about 270°) and different wind turbine settings (phase 1, 2 and 3) the relation between the mast anemometer and the nacelle anemometer was quite varying. Therefore, if the wind turbine settings are changed not only the power output changes, but also the nacelle anemometer readings are changed.

With the wind turbine stopped it was found that the nacelle anemometer measured 20-30% higher wind speeds than the mast anemometer, which means that the nacelle presence influences the flow around the nacelle. The wind speed 3m above the roof was higher than at 1.2m. This shows that the induced flow around the nacelle extends quite far from the nacelle, which indicates that the nacelle design has a substantial influence on the reading of the nacelle anemometer.

In conclusion, it can be said that provided the following factors remain unchanged:

- the wind turbine rotor settings
- the wind turbine's yaw error
- the anemometer's position on the nacelle
- the terrain is flat

then the relation mast-nacelle anemometer can be can be transferred between wind turbines of the same make and type. Under these conditions the "corrected" nacelle anemometer can be used for the verification of the turbine's power curve and the AEP.

Whether and under which conditions this relation is transferable from one kind of terrain to another (e.g. from flat to complex) remains to be investigated as the lack of data on this subject prevents us from drawing any conclusions.

8. References

1. "Trends in Power Performance Measurement Standards", T.F. Pedersen, AWEA 94

2. "Konceptundersøgelse NORDTANK NTK500/41, Structurelle laster -Tårnbøjning", S.M. Petersen, Risø-I-786(DA), 1994.

3. "Power Performance Measurement by means of an anemometer located on the nacelle", C. Hinsch, D. Westermann, DEWI Technical Note 19.08.96.

4. "Power Performance Measurement Techniques for Wind Farms", J.T.D. Slater, RES Document 500/RES/1117, 1996.

5. "Elkraft 1MW Vindmølle I Avedøre", Provestationen for Vindmøller, Risø, 27 januar 1994.

6. "Recommendation for Wind Turbine Power Curve Measurements", T.F. Pedersen (ed.), Risø-I-745(EN), November 1993.

7. "Wind Turbine Test: Structural Loads ELKRAFT 1MW (Stall Regulated Operation)", I. Antoniou, S. M. Petersen, Risø-I-865(EN), 1995.

8. "Recommendations for a European Wind Turbine Standard on Performance Determination", A. Curvers, T.F.Pedersen, ECN-217, July 1989.

9. "Separationsmønsteret for et LM19.1 Blad", P. Fulsang, Resultatblad AED_RB_2, Risø, 1996

10. "European Wind Atlas", Ib Troen and Erik Lundtang Petersen, Risø 1989.

Bibliographic Data Sheet **Risø-R-941(EN)**

Title and authors

Nacelle Anemometry on a 1MW wind turbine: Comparing the power performance results by use of the nacelle or mast anemometer

Ioannis Antoniou, Troels Friis Pedersen

ISBN	ISSN
87-550-2323-1	0106-2840

Department or group	Date
The Test Station for Wind Turbines Dept. of Meteorology and Wind Energy	August 1997

Groups own reg. number(s)	Project/contract No(s)
	VIM 03639-00(internal proj. number) JOR-CT95-0064 JOR-CT96-0114

Pages	Tables	Illustrations	References
34	6	26	10

Abstract (max. 2000 characters)

The report describes measurements carried out on the ELKRAFT 1MW wind turbine in the period from week 46 / 1994 to week 10 / 1997. The correlation between the mast and the nacelle anemometer is investigated and the result of the power curve measurements is presented as a function of both the mast and the "corrected" nacelle anemometer. The scope of this is to gain a better understanding on the merits and limitations of the use of the nacelle anemometer as an alternative to the mast anemometer for the verification of the turbine's power curve and the calculation of the annual energy production. Data collected from three phases of operation and two nacelle anemometer height positions is shown and compared with each other in the present report. During the first phase the turbine blades are set at a pitch angle of +0.5° (nacelle anemometer at 1.2m height). During the second phase the turbine blades are also set at a pitch angle of +0.5° and a new yaw condition is introduced in order to reduce the turbine's yaw error (nacelle anemometer at 1.2m height). Finally, during the third phase, the pitch angle of the blades is set to -1.0° and vortex generators are placed in the inner part of the blades (nacelle anemometer at 1.2m and 3m height). Following the above analysis conclusions, concerning the limits on the use of the nacelle anemometer as an alternative for the power curve measurements, will be drawn.

Descriptors INIS/EDB

ANEMOMETERS; HORIZONTAL AXIS TURBINES; POWER GENERATION; PERFORMANCE

Available on request from Information Service Department, Risø National Laboratory,
(Afdelingen for Informationsservice, Forskningscenter Risø), P.O.Box 49, DK-4000 Roskilde, Denmark.
Telephone +45 46 77 40 04, Telefax +45 46 77 40 13