PERFORMANCE TESTING OF A 50 kW VAWT IN A BUILT-UP ENVIRONMENT.

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ABSTRACT

The results of performance tests of a DAF Indal 50 kW vertical axis wind turbine carried out at the Company's plant near Toronto, Canada, are presented. Results of limited free stream turbulence and vertical wind shear measurements at the site are also presented. The close agreement between measured and predicted energy outputs, required to verify the wind turbine power output performance relationship, was not attained. A discussion is presented of factors that may have contributed to the lack of better agreement.

INTRODUCTION

Free stream performance testing of a DAF Indal 50 kW vertical axis wind turbine was carried out at the Company's plant in Mississauga, Ontario, Canada under contract to the National Research Council of Canada. The wind turbine was erected at the plant in February, 1980, for pre-delivery trials.

The installation site (Figure 1) did not exhibit unobstructed exposure or strong and steady winds. In addition, the time available for testing was limited because the "windy" season usually ends in April. However, the urgent need for reliable performance data and the advantage of immediate access to the wind turbine weighed heavily in the decision to proceed with performance testing.

WIND TURBINE

The DAF Indal 50 kW vertical axis wind turbine (Figure 2) was designed as a demonstration machine for parallel operation with electrical power networks. The characteristics of the unit tested are given in Table I.

The induction generator can be operated in both the wye and delta winding configurations to take advantage of the reduced generator losses in wye at low power outputs. The control system commands a change from wye to delta when the power output exceeds about 30% of the rated generator output. The control system also disconnects the generator from the network when the rotor speed drops below the synchronous speed, to minimize motoring. The control functions described were overridden during performance testing so that data could be gathered for operation in both wye and delta, above and below the power production threshold wind speeds.

TEST SITE

The test site is shown schematically in Figures 3 and 4. The location of the wind turbine was determined by the fact that the guy anchor footings had to be on the Company's property. The base of the wind turbine rotor was at approximately the same elevation as the roof of the DAF Indal plant building.

The plant is located in a light industrial and warehouse area. Most of the buildings are between four and 10 meters high, and many have floor areas of several thousand square meters. The DAF Indal plant is 10m high and occupies an area of almost 10,000 square meters.

The closest obstructions to the wind turbine were the plant building and the test platform building (approximately 7m high) as shown in Figures 1 and 3. Large buildings, about 10m high, were located approximately 120 meters northeast, 120 meters north and 80 meters northwest of the wind turbine. In addition, construction staging (16m high), that had been installed to gain access to the spoilers, remained in place during the tests, seven meters south of the rotor axis, just clear of the rotor.

The anemometer tower was installed 18 meters west-southwest of the rotor, in order to be generally upwind during the relatively strong wind periods in February, March and April, based on long term data for the nearby Toronto International Airport. At this distance, the upwind free stream should not be significantly influenced by the flow through the rotor (ref.1).

Anemometers were installed at 10.5m and 18.3m above the base of the tower. The upper anemometer, used exclusively for performance testing, was 1.9m above the rotor equator. The lower anemometer was used for wind shear measurements only.

INSTRUMENTATION

Wind turbine power output performance data, performance verification data and some data describing the characteristics of the free stream were gathered. An instrumentation schematic is shown in Figure 5.

A rotating disc watthour meter recorded the net energy output or consumption of the wind turbine. Wind speed was recorded by a wind histogram recorder, which measured two second average wind speed continuously and incremented the appropriate bin counter (0.5 m/s bin widths). One second average wind speed was also displayed digitally.

Both cup anemometers were identical and of research grade, with a manufacturer's quoted response distance constant of 1.52 meters.

TEST METHOD

Performance data were recorded when the anemometer was believed to be outside of the influence of the flow through the rotor. Although the anemometers were positioned to be upwind of the rotor for the predicted strong wind directions, it turned out that during the period of testing, the strongest winds blew over one half the time from the directions such that either the anemometer was immersed in the rotor wake, or the wake of the main plant building. As a result, the periods during which performance data could be collected were very short. Most of the data were recorded during the passage of storms. Wind direction changes of about 15 to 30 degrees were commonly observed as strong gusts developed. Given these conditions, it is probable that some performance data, later used to define the performance curves, were acquired while the anemometer was influenced by the rotor wake, even though care was taken to eliminate such data.

The wind speed frequency distribution (or wind histogram) and the elapsed time were recorded for an exact number of watthour meter disc increment markers (100/rev.) to pass a reference mark. The elapsed time for each test run was typically between five and 25 seconds. Measurements were made when the disc speed was thought to be steady, and the wind speed and power output were thought to be reasonably well correlated. The method turned out to be tedious and time consuming.

The wind turbine performance could not be well defined for wind speeds in excess of about 14 m/s because operation was restricted to wind speeds less than 16 m/s pending the analysis of experimental blade stress data. (The wind turbine actually did operate at speeds in excess of 16 m/s for very short periods, during gusts).

Barometric pressure and temperature were recorded for each series of test data.

Performance verification data were recorded in the same manner as the performance data except that the test runs were several minutes, rather than several seconds, in duration.

Wind shear data were gathered by simultaneously recording the wind speed frequency distributions measured by the two anemometers for periods of between one half and four minutes. Alongwind turbulence data consisted of wind speed frequency distributions measured by the upper anemometer for periods of up to 15 minutes.

PERFORMANCE TEST RESULTS

A total of 416 and 212 useful data sets were acquired in the delta and wye generator configurations respectively. The wind histogram record for each set was reduced to the effective cubic weighted average wind speed for the test period (i.e. the steady wind speed having the energy equal to that represented by the actual wind speed frequency distribution for the test run). The average power output for each test run was proportional to the number of disc increments recorded, divided by the elapsed time.

Two random data analysis methods were used to determine the power output versus wind speed relationships.

(1) The method of bins (ref. 2 and 3). Here the data sets were grouped into wind speed bins (0.5 m/s width) and the average power was determined for each bin. The results for wye and delta are shown in Figures 6 and 7 along with best fit curves. These curves intersect at about 7.5 kW which is unexpectedly low. Data in the wye configuration were limited to power outputs below about 12 kW because the slip of the generator is such that at higher power outputs the wind turbine automatically shuts down due to overspeed.

The test data were also binned by power; the results are shown in Figures 8 and 9. To the knowledge of the author, power binning has not been proposed previously. The results for power and wind speed binning are in good agreement except for delta configuration at power outputs greater than 30 kW.

The measured standard deviation is shown for each bin. These indicate the combined effects of the imperfect correlation between measurements of power and wind speed and the error in the individual power and wind speed measurements. The correlation effect dominates, since the power measurement error was estimated to be less than nine percent and the wind speed measurement error was estimated to range from 16 percent at two m/s to only three percent at 15 m/s.

(2) The method of frequency matching (ref. 3). Here the power curve is defined as the sets of measured power and wind speed points which have equal cummulative probabilities. The results of frequency matching are shown in Figures 10 and 11. There is seen to be good agreement between these data and the best fit curves for wind speed binning.

WIND SHEAR AND TURBULENCE TEST RESULTS

Alongwind RMS turbulence (gustiness) can be estimated using wind speed frequency distributions of several minutes duration. The ratio of the standard deviation to the average wind speed is a measure of the alongwind RMS turbulence intensity.

Data were recorded using the upper anemometer (18.3 m). Test runs were grouped by wind direction in order to investigate the effect of surrounding structures. The results of the data analysis, shown in Table II, are consistent with other published turbulence data for the same general surface features. There does not appear to be any significant correlation between turbulence intensity and wind direction (i.e. surrounding structures) at the measurement height of 18.3 meters. The turbulence intensity in the rotor wake, measured 18 meters from the rotor axis, is approximately twice that measured in the free stream.

The results of the wind shear data analysis are shown in Table III. The value of the power law exponent in each case was based on linear regression of the upper anemometer average wind speed on the lower anemometer wind speed.

The measured power law exponents appear to correlate with the proximity of the structures upwind of the anemometers. The exponent for northeast winds is the lowest of those measured, consistent with the unobstructed exposure for more than 120m upwind. The exponents for northwest winds are somewhat higher than those recorded for the northeast, indicating the effect of the building lying about 70 meters upwind. The exponents for south winds are the second highest recorded, clearly showing the influence of the west corner of the DAF Indal plant building lying about 50m upwind.

The measured power law exponents for southwest winds are unusually high, indicating the large shear in the near wake of the test platform building lying 10 meters upwind of the anemometers. Although 42 performance data points (wye and delta combined) were collected while the wind was from the southwest, it is believed that the overall effect on the performance curves was small.

POWER OUTPUT PERFORMANCE VERIFICATION

The validity of wind turbine power output performance curves is determined by comparing measured energy outputs (ideally for periods of at least several hours) to those calculated using the relationship.

$$E = T \int_{V_1}^{V_2} F(V)P(V)dV \text{ where}$$

F(V) is the measured probability density of wind speed, P(V) is the measured wind speed power output function, V_1 and V_2 are the wind speed limits for the test period, and T is the elapsed time.

Verification test runs were carried out for durations of several minutes only; the measured and calculated outputs are shown in Table IV. Calculated values are based on the curves shown in Figures 6 and 7. (Data from several performance verification test runs could not be used because the wind speed frequency distributions included wind speeds above which the performance curves are not defined).

The agreement between measured and predicted energy outputs is sensitive to the assumed best fit positions of the performance curves. However, it is probable that other factors contributed in part to the difference between the measured and calculated values.

(1) A significant portion of the test data used to define the performance curves could have been acquired while the anemometer was influenced by the rotor wake, even though care was taken to eliminate such data. The effect of a shielded anemometer is to shift the performance curves to lower wind speeds; therefore calculated energy outputs, based on these curves and the measured wind speed distributions, will be too high. Figure 12 shows data acquired with the anemometer known to be shielded. The effect of anemometer shielding is also shown in Table IV which includes the results of two performance verification test runs carried out with the anemometer in the wake of the rotor.

(2) The wind field at the test site would be perturbed because of the buildings surrounding the wind turbine (ref. 4 and 5). Therefore the wind speed distributions measured by the anemometer during the short performance verification test periods may have been significantly different than those experienced by the wind turbine.

The closest obstructions to the wind turbine were in the sector east to south-west of the rotor, which coincides with the two poorest performance verification test results. Power output and wind speed were frequently observed to be uncorrelated for periods of up to 10 seconds, except with the anemometer directly upwind of the rotor. The magnitude of the measured power output standard deviations confirms these observations (Figures 6 and 7). They are about ten times greater than those reported from tests of a Grumman Windstream 25 wind turbine (ref.3) at Rocky Flats, Colorado based on 30 second average data, and a DAF Indal 50 kW mechanically coupled vertical axis wind turbine near Bushland, Texas (ref. 6) based on 15 second average data. Both sites have unobstructed exposure.

It was also observed that the wind turbine power output did not follow wind speed fluctuations of two to three m/s having durations of five seconds or less (based on continuous one second averages) even with the anemometer upwind and taking into account a time delay. This suggests that, in the perturbed flow, a significant fraction of the wind energy was not captured because it was associated with frequencies above the wind turbine response cut off frequency (ref.7).

CONCLUDING REMARKS

The problems associated with wind turbine testing in a turbulent wind were amplified because of the effect of surrounding structures. Nevertheless performance curves for the DAF Indal 50 kW vertical axis wind turbine were obtained. The results of the performance data analysis, using the method of bins (wind speed binning) and the method of frequency matching are in good agreement. The close agreement between measured and predicted energy outputs required to verify the performance curves was not attained. The characteristics of the perturbed wind stream are believed to be partly responsible for the lack of better agreement.

The measured turbulence intensities (based on two second average wind histogram records) were consistent with other data for similar terrain features. The results of wind shear measurements did correlate with the position of surrounding structures and provided strong evidence of the effect of these structures on the wind stream seen by the wind turbine.

The benefit of wye to delta generator winding changes was found to be significantly less than expected. However, free stream wind turbine testing is an indirect technique for determining the loss characteristics of an induction generator. A small shift in the position of either the wye or delta performance curve will result in a significantly different point of intersection.

Although the wind and site conditions hampered data acquisition, the manual data acquisition method that was used may be more successful at other unobstructed test sites experiencing strong and steady winds.

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6. Personal Communication, R.N. Clark, U.S.D.A. South-Western Great Plains Research Center, Bushland, Texas.

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Table I

DAF Indal 50 kW Vertical Axis Wind Turbine
Description of the Unit Used for Performance Testing

Generic Description

Vertical axis wind turbine generator Darrieus Type. Troposkien blade shape.

Rotor

Number of Blades	2
Height	16.8 m
Diameter at Equator	11.1 m
Capture Area	121 m^2
Speed	80 rpm
Rotor Column	0.6 m dia. steel pipe
Weight	3100 kg
Struts	2

Blades

Material	Extruded aluminum alloy
Airfoil	NACA 0015
Chord	0.36 m

Transmission

Type	Single stage spur gear (bull gear) and pinion. Spray lubricated. Vertical shafts.
Ratio	15

The bull gear also serves as the brake disc.

Generator

Type	Induction
Rating	56 kW
Voltage	575 V three phase
Speed	1200 rpm
Frequency	60 Hz

The generator also serves as the starting motor

Overspeed Control

Primary control by means of the rotor mounted automatic disc brake. Secondary control by means of aerodynamic spoilers mounted on the blades and deployed automatically

TABLE II

Alongwind Freestream Turbulence Test Results

Wind Direction	Total Number of Test Runs	Average Wind Speed at 18.3m (m/s)	Average Alongwind RMS Turbulence at 18.3m
NE	3	4.6	0.15
NNW	5	6.2	0.18
NW	11	9.5	0.18
SW	3	5.4	0.18
S	2	6.1	0.21
*NE	1	7.8	0.35
*NE	1	9.9	0.37
*NE	1	10	0.28
*NE	1	10.4	0.30

* Anemometer in the rotor wake.

TABLE III

Wind Shear Test Results

Wind Direction	Total Number of Test Runs	Range of Average Wind Speed for the Upper Anemometer (m/s)	Wind Shear Power Law Exponent Determined by Linear Regression
NE	10	3.4 to 5	0.14
NW	12	4.4 to 6	0.18
	15	6 to 8.5	0.23
	27	4.4 to 8.5	0.21
SW	15	4.2 to 6	0.32
	14	6 to 8.4	0.52
	29	4.2 to 8.4	0.47
S	5	2.6 to 6.1	0.22
	7	6.1 to 8.3	0.28
	12	2.6 to 8.3	0.26

Table IV

Performance Verification Test Results

Generator Winding Configuration	Duration Test Run (T) in Minutes	Wind Speed Range in m/s V_1	V_2	Wind Direction	Measured Energy in kWh*	Calculated Energy (E) in kWh**	Ratio of Measured to Calculated Energy
Wye	7.1	4.3	9.8	W	0.23	0.33	0.70
	19.8	2.8	9.8	S	0.23	0.40	0.58
	13.3	3.8	10.2	SW	0.53	0.85	0.62
	11.8	3.8	10.2	W	0.59	0.72	0.82
	5.2	5.8	10.2	NW	0.59	0.67	0.88
Delta	6.7	4.3	9.8	W	0.35	0.39	0.90
	7.1	3.8	11.3	NW	0.47	0.56	0.84
	7.0	4.3	9.8	NW	0.41	0.52	0.79
	6.0	4.8	10.7	NW	0.58	0.71	0.82
	5.8	5.3	10.7	NW	0.58	0.79	0.73
	12.9	4.8	13.7	NW	2.61	3.12	0.84
	29.2	3.8	13.2	NW	3.79	4.45	0.85
	•10.7	3.3	16.2	NE	4.60	2.12	2.17
	•11.6	3.3	16.2	NE	5.06	3.45	1.47

• Anemometer in the wake of the rotor.

** Determined using the curves in Figures 6 and 7.

* Corrected to freestream air density of 1.253 kg/m³.

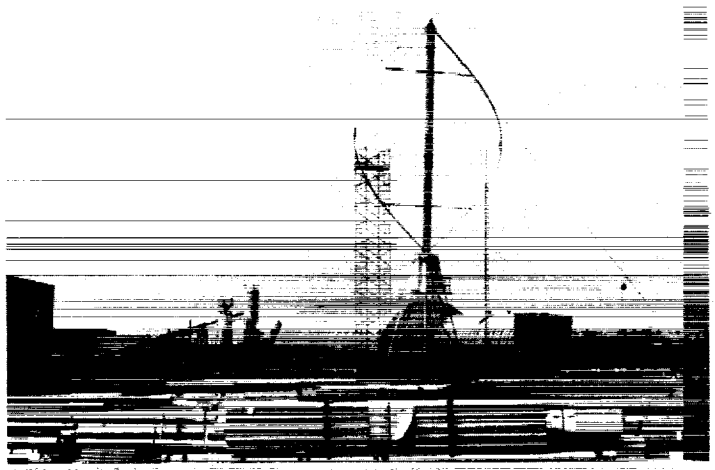

Figure 1 VIEW OF THE TEST INSTALLATION SITE LOOKING SOUTHWEST

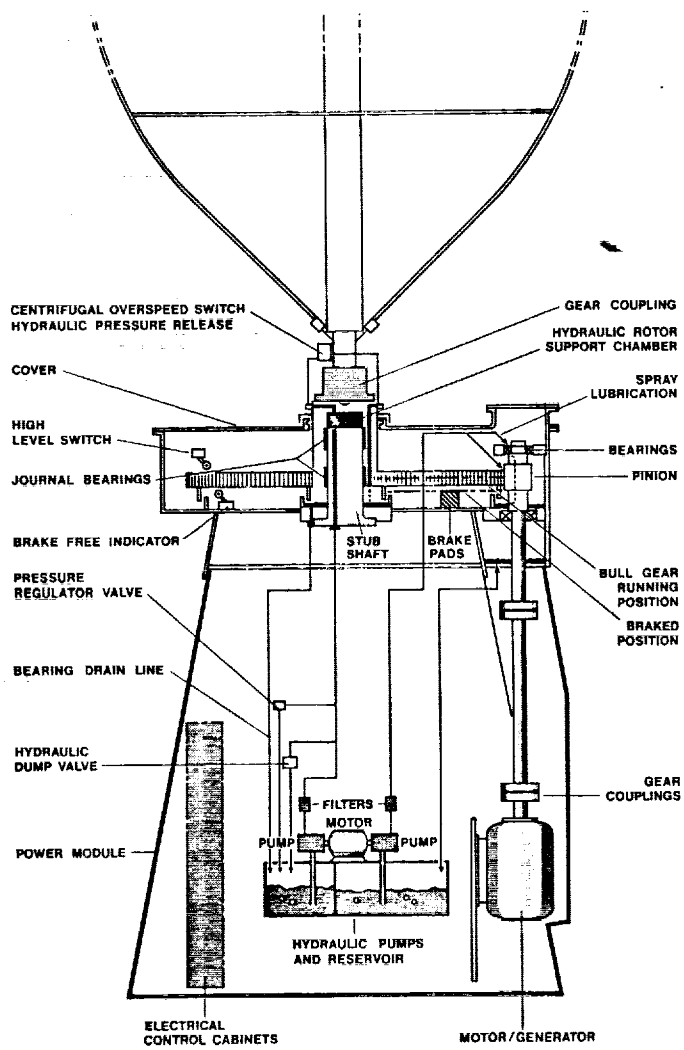

Figure 2 SCHEMATIC OF THE DAF INDAL VERTICAL AXIS WIND TURBINE

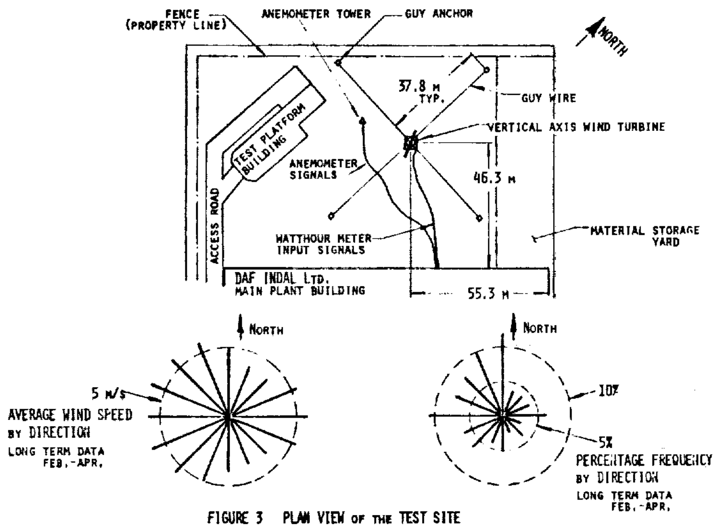

FIGURE 3 PLAN VIEW OF THE TEST SITE

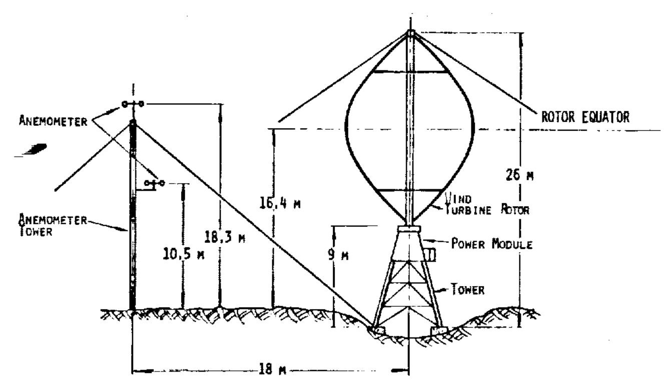

FIGURE 4 SCHEMATIC OF THE TEST INSTALLATION

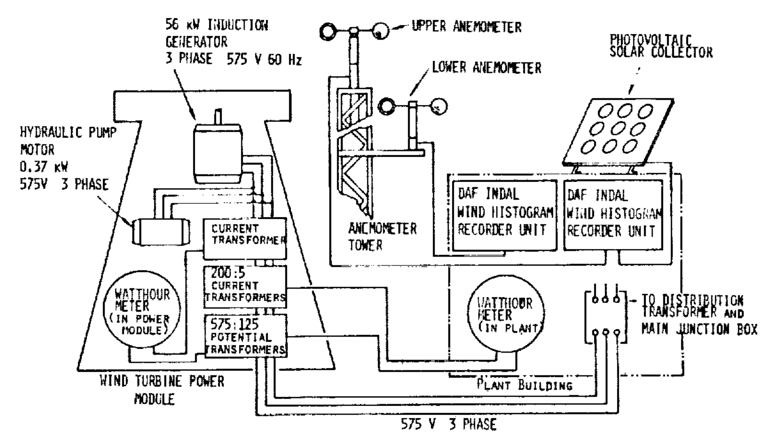

FIGURE 5 TEST INSTRUMENTATION SCHEMATIC

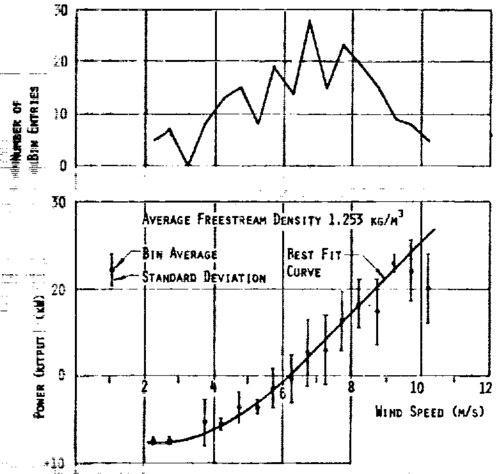

FIGURE 6 POWER OUTPUT IN WYE (WIND SPEED BINNING)

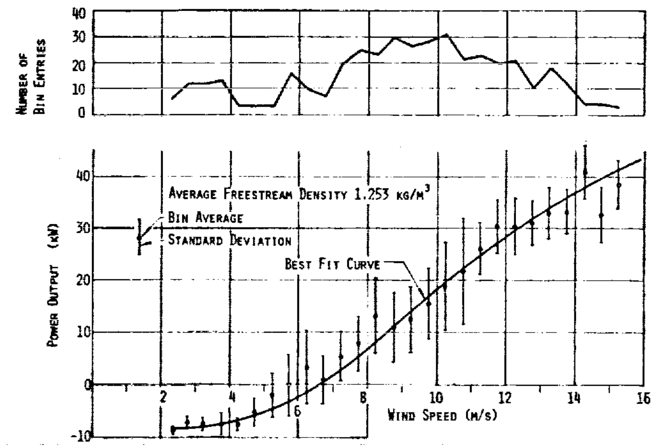

FIGURE 7 POWER OUTPUT IN DELTA (WIND SPEED BINNING)

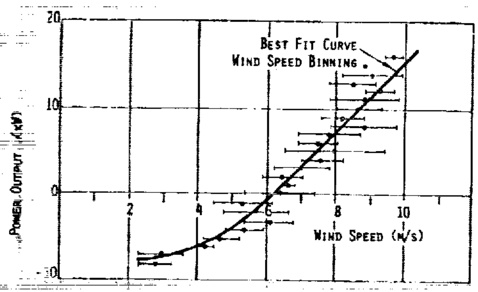

FIGURE 8 POWER OUTPUT IN WYE (POWER BINNING)

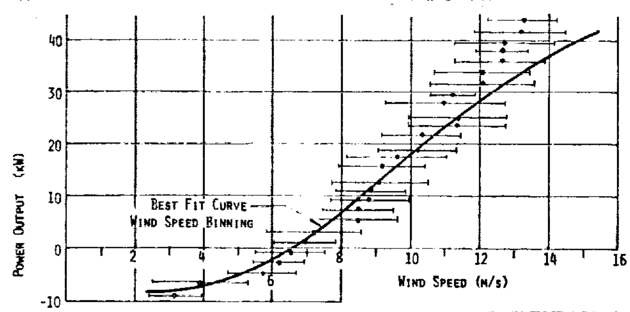

FIGURE 9 POWER OUTPUT IN DELTA (POWER BINNING)

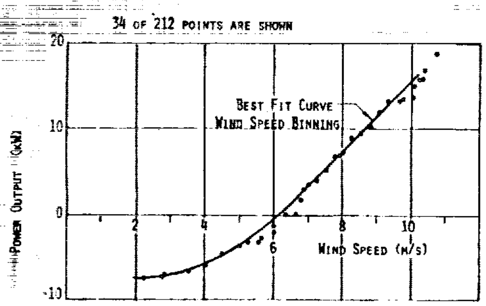

FIGURE 10 RESULTS OF FREQUENCY MATCHING OF WYE DATA

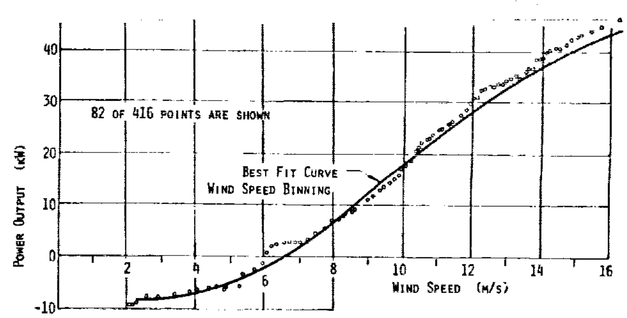

FIGURE 11 RESULTS OF FREQUENCY MATCHING OF DELTA DATA

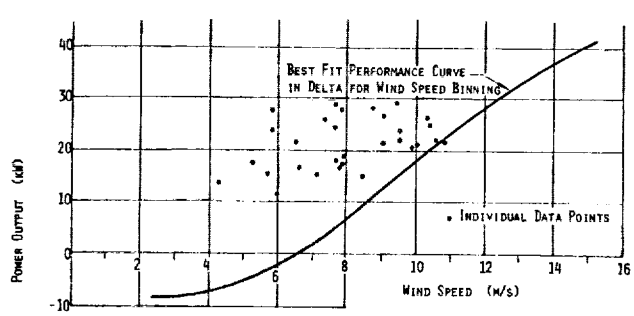

FIGURE 12 PERFORMANCE DATA SHOWING THE EFFECT OF ANEMOMETER SHIELDING

QUESTIONS AND ANSWERS

L.A. Schienbein

From: Bill Wentz

Q: How is your spoiler actuated?

A: *The spoilers are latched by electromagnets installed in the blades. When overspeed is sensed, the current to the electromagnets is interrupted and each spoiler deploys as the result of a combined aerodynamic and centrifugal moment.*

From: Tom Bellows

Q: Why did you not put the anemometer on top of the rotor tower?

A: *This was considered. We were advised by others who had mounted anemometers above the rotor, that anemometer maintenance was a problem and that anemometer life would be substantially reduced. Furthermore, given the nature of the test site, we believed that it would not be possible to reliably correct the measured wind speeds to the rotor equator height.*

From: R. Edkin

Q: During your wind turbine operation, did you experience any problems using an induction generator? With Wye or Delta connections?

A: *No to both questions.*