CALCULATION OF GUARANTEED MEAN POWER FROM WIND TURBINE GENERATORS

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ABSTRACT

Much research has been devoted to the nominal power generated by wind machines, but little work has been done on the subject of guaranteed power. Yet power guarantees will be part of the commercialization of wind energy systems. This paper describes in step-by-step fashion a proposed method for calculating the "guaranteed mean" power output of a wind turbine generator. The term "mean power" as used in this study refers to the average power generated at specified wind speeds during short-term tests. Extrapolation to an annual mean power, based on wind statistics, is beyond the scope of this paper. Guaranteed energy is not addressed. The DOE/NASA Mod-OA 200 kW plant in Clayton, New Mexico, is used as a sample case. Subjects discussed and illustrated are correlation of anemometers, the method of bins for analyzing non-steady data, the PROP Code for predicting turbine power, and statistical analysis of deviations in test data from theory. Guaranteed mean power density for the Clayton Mod-OA system was found to be 8 watts per square meter less than theoretical power density at all power levels, with a confidence level of 0.999. This amounts to 4 percent of rated power.

INTRODUCTION

As the commercialization of wind turbine generators progresses, there will be increased demands by purchasers for guarantees on power output. Such guarantees are common for thermal and nuclear power plants, and there is no reason to believe that wind power plants will be an exception. However, guaranteeing the performance of a wind energy system presents two major problems which sellers of conventional plants do not have to face. First, unlike conventional fuels, the energy content of the wind "fuel" is not easy to sample. Second, wind turbines normally operate in a transient state, unlike conventional plants which can be placed in a steady state in practice as well as in theory. Thus, the developers of wind energy systems are faced with both the requirement of guaranteeing system performance and substantial difficulty in satisfying that requirement.

Methods for predicting the nominal power output of a wind turbine have been studied extensively and reported in detail. A recent comprehensive review of almost 140 references on the aerodynamic behavior of wind energy systems is given in reference 1. However, the subject of a guaranteed power output does not seem to have been addressed in the literature. This is not surprising since guarantees imply commercialization, field test experience, and statistical analysis of data, all of which are rather recent additions to the wind energy field. The major purpose of this paper, then, is to stimulate discussion and publication of guaranteed as well as nominal performance data for wind energy systems. In addition, a proposed procedure is made available now to the analyst who is in the process of predicting wind turbine power for guarantee purposes.

The term "mean power" as used in this study refers to the average power generated at specified wind speeds during short-term tests. Extrapolation to an annual mean power, based on wind statistics, is beyond the scope of this paper. Guaranteed energy is not addressed. The proposed procedure for arriving at a guaranteed power will be described and documented by means of a sample case. The DOE/NASA Mod-OA 200 kW wind turbine generator will be used in this example. The design of this machine is described in detail in reference 2. While the Mod-OA is a large horizontal-axis wind turbine, procedures described in this paper may apply equally well to vertical-axis and small horizontal-axis wind turbine generators.

PROCEDURE

Most wind turbine generator systems can be represented by the schematic diagram shown in Figure 1. This idealized figure is the basis for many of the terms used later to describe measurements, calculations, and results. The system consists of a turbine, a transmission, and a generator, with a wind power input and wind, thermal, and electrical power outputs. For reference to measurement points, the system is divided by stations, in accordance with usual practice in analyzing fluid flow. Station 0 is along the turbine midline and far enough upwind to be undisturbed by the turbine. An anemometer is required at Station 0 to measure free-stream wind speed. An anemometer at Station 1 would measure turbine input wind speed, while turbine output wind speed would be measured at Station 2 on the midline. The turbine output shaft is also at Station 2, though it may actually be located upwind of the turbine. Stations at the output shafts of successive stages in the transmission are designated 2.1, 2.2, etc. Any of these shaft stations could be the location of torque and speed sensors. System electrical output and wind output occur at Station 3. Thermal output from power-train losses occurs between Stations 2 and 3. The station numbers in Figure 1 follow the usual notation for one-dimensional aerodynamic analysis.

Test Installation

Figure 2 illustrates the relative locations of the Mod-OA 200 kW wind turbine generator and its auxiliary anemometer tower, outside Clayton, New Mexico. The anemometer tower is approximately 50 meters to the southwest of the wind turbine in the direction of the prevailing wind. The anemometer at Station 0, at the 30 meter elevation on the turbine midline, measures the free-stream wind speed. A second anemometer is located just upwind of the rotor, at Station 1, and measures the turbine input wind speed. Turbine shaft torque and shaft speed are measured by sensors located at Station 2, between the turbine and the gearbox. Generator output is measured at Station 3, in the ground control enclosure.

Calculation Steps

The procedure for calculating guaranteed power will be divided into eight steps, as follows.

1. Correlation of free-stream and turbine input (or output) anemometers, located at Stations 0 and 1 (or 2), respectively.
2. Correlation of performance test data taken at various stations, such as wind speed at Station 1 with shaft torque and speed at Station 2, and with electrical power at Station 3.
3. Calculation of wind power input concurrent with test data, using the correlation obtained in step 1.
4. Calculation of theoretical turbine output power.
5. Analysis of deviations between measured and theoretical turbine output power.
6. Estimation of lower bound on the mean deviation from theory, for a specified confidence limit.
7. Analysis of power-train losses.
8. Calculation of guaranteed mean power output, for the turbine and the system.

Each of these steps is illustrated by means of a sample calculation for the Clayton Mod-OA wind turbine generator.

Method of Bins

Much of the data analysis in this study was done using the "method of bins", a statistical procedure (ref. 3) which has been used extensively to reduce wind turbine data (refs. 4, 5, and 6). For the purposes of this study, application of the method can be summarized as follows:

1. A "bin" is a data storage unit labeled with a nominal wind speed and containing a compartment for each sensor. Nominal wind speeds are selected to cover the operating range at intervals of 1.0 meter per second. In this study there are 15 wind speed bins each with four sensor compartments.

2. For each rotation of the turbine rotor (a period of 1.5 sec.) average readings from all sensors are stored in the same bin, in their respective compartments. The bin is selected according to the turbine input wind speed.

3. Median values are calculated for the contents of each compartment in each bin. Thus, the data set for this study was reduced to 60 compartment median values.

4. Compartment median values are assumed to be concurrent. No assumption is made concerning the concurrence of any data values other than the compartment medians.

The method of bins has been found to be particularly useful for the non-steady conditions under which wind energy systems operate. Correlation between data from sensors on the machine and data from anemometers placed away from the machine is generally improved when the method of bins is used in place of time coincidence.

CALCULATIONS, RESULTS, AND DISCUSSION

Step 1: Correlation of Free-Stream and Turbine Anemometers

With the wind turbine producing on-line power, simultaneous measurements of free-stream wind speed and turbine input wind speed were taken and analyzed using the method of bins. The resulting pairs of compartment median wind speeds were then cross-plotted as shown in Figure 3. Each data point in this figure represents one bin of data with a speed range of 1.0 meter per second, measured at the turbine input. Eight separate operating periods are included, totaling 26.4 hours and over 63,000 pairs of measurements. Bins at wind speeds more than 1.0 meters per second above rated have been eliminated because pitching the blades changes the trend of the data. Also, a correlation equation at wind speeds above rated is not required for efficiency calculations.

Regression analysis was used to fit a correlation line to the data in the following form:

$$V_0 = a + bV_1, \quad m/s \tag{1}$$

V_0 and V_1 are the median values of bins of free-stream and turbine input wind speeds, respectively. The empirical constants for the Clayton Mod-OA wind turbine are as follows:

and $a = 3.39$ m/s

$b = 0.667$

The scatter about the curve-fit line in Figure 3 can be attributed to variations in wind direction, yaw heading errors, and turbulence. This amount of scatter is to be expected, and therefore the data set must be large enough to randomize the variations. In addition, the machine must be operating as designed at all wind speeds, in order to produce the correct retardation in the free-stream wind speed.

Step 2: Correlation of Performance Test Data

Table I lists all the performance test data which were used in this study to calculate the guaranteed mean power of the Clayton Mod-OA wind turbine. These data were recorded during (a) 2.2 hours of on-line operation on January 10, 1978, (b) 4.6 hours of on-line operation on January 18, 1978, and (c) during a shop run-in test of a similar unit in December 1979. The latter data will be referred to during calculation of power-train losses.

The method of bins, as incorporated in the NASA data system (ref. 6), reduces a large data set to a concise summary while maintaining acceptable correlation and accuracy. Though Table I is brief, it contains bin compartment medians calculated from over 65,000 separate measurements. For each wind speed bin, 1.0 meter per second in range, the following median values of data in corresponding compartments are required for this analysis:

1. Turbine input wind speed V_1, measured at Station 1 (see Fig. 2 for stations).
2. Turbine shaft torque Q_2, measured at Station 2.
3. Turbine shaft speed Ω_2, measured at Station 2.
4. Generator output power P_3, measured at Station 3, in the ground control enclosure.

The bins are numbered for later reference in successive tables.

No special machine operations were performed to obtain the on-line data in Table I. Data were recorded during the initial 100-hr acceptance test of the machine, under normal utility operating conditions. Records 1 and 2 each contain at least one start-stop transient operation, which can be accommodated automatically by the data analysis system.

Step 3: Calculation of Wind Power Input

"Wind power input" refers to the power density of the free-stream wind at the turbine midline (Fig. 1), expressed in watts per square meter. All efficiency values are referenced to this wind power density, which is calculated according to the following fundamental equation:

$$P_0 = \frac{\rho}{2} V_0^3, \quad W/m^2 \qquad (2)$$

The free-stream wind speed V_0 in this equation is calculated for each bin using Equation (1) and the turbine input wind speeds V_1 from Table I. The results are listed in the second column of Table II.

The air density ρ in Equation (2) should be calculated from temperature and barometric pressure measurements made during the recording of power data. Use of Standard Atmosphere density data is not recommended. As shown in Figure 4, there is about a 5 percent difference between Standard Atmosphere density for the Clayton midline elevation and the actual densities at the time of the two test runs. This difference is too large for efficiency calculations. The average local air density of 1.101 kilograms per cubic meter was used to calculate the free-stream wind power densities listed in the third column of Table II.

Step 4: Calculation of Theoretical Turbine Output Power

The calculation of guaranteed mean power is essentially a calibration of a specified theory for predicting the aerodynamic performance of a wind turbine. As mentioned previously, there are a variety of such theories available (ref. 1). Without questioning the validity of various theories, it is clear that deviations between test data and theory will differ for different theories, leading to different calibrations. Therefore, it is important to specify the theoretical method used as a basis for predicting guaranteed mean power.

In this study, theoretical turbine output power was calculated by means of the PROP Code, described in references 7, 8, and 9. This code is in the public domain, and the references present the theoretical basis for the computational procedures in it. Quasi-static aerodynamic behavior is assumed. Data for the NACA 23000 series airfoils on the Mod-OA turbine were obtained from reference 10. Lift and drag coefficients for smooth and standard roughness airfoils were averaged, to approximate a NASA roughness condition.

The fourth, fifth, and sixth columns in Table II list the results of theoretical calculations of turbine output power for each bin. The tip-speed ratio is calculated from the equation

$$\lambda = R\Omega_2/V_0 \qquad (3)$$

in which the radial dimension R is 18.9 meters (including the effect of 7 degrees of coning), and the turbine shaft speeds Ω_2 are given in Table I.

Theoretical turbine efficiency is a function of λ and is independent of the air density. However, the turbine power density does depend on air density and is calculated as follows:

$$p_{2,th} = E_2 p_0, \quad W/m^2 \tag{4}$$

Step 5: Analysis of Deviations from Theoretical Power

Experimental turbine power densities are listed for each bin in the seventh column of Table II. To calculate turbine power density from the data in Table I, the following equation is used:

$$p_2 = Q_2 \Omega_2 / A, \quad W/m^2 \tag{5}$$

The constant A is the swept area of the turbine, equal to 1123 square meters for the Mod-OA rotor. Experimental turbine efficiency was then calculated by dividing turbine power output by wind power input, as follows:

$$\eta_2 = p_2/p_0 \tag{6}$$

Experimental and theoretical peak efficiencies were found to be approximately the same and equal to 0.41.

Experimental turbine efficiencies are compared with theory in Figure 5. Theory is shown by the dashed line, and the solid line denotes a power output controlled to 200 kilowatts. The latter portion of the efficiency curve does not depend on theory. Therefore data at rated power have been deleted from Figure 5.

In general, the correlation shown in Figure 5 is good between experiment and theory. However, a quantitative measure of the correlation is required before guaranteed mean power can be calculated. To obtain this quantitative assessment, deviations from theoretical turbine power density are calculated as follows:

$$\delta p_2 = p_2 - p_{2,th}, \quad W/m^2 \tag{7}$$

The ninth column in Table II contains the power density deviations for the test data sets.

To simplify the statistical analysis which will follow, a random distribution of deviations is desirable. Two tests for randomness were performed. First, the deviations from theory in Table II were plotted versus the corresponding theoretical turbine power densities, as shown in Figure 6(a). No trend in the data was observed. Therefore, it is consistent with these test data to assume that deviations from theoretical power predicted using the PROP Code theory do not depend on power density, at least up to levels of 200 watts per square meter.

Next, the probability distribution of the deviations was calculated, leading to the results which are illustrated in Figure 6(b). A straight line on this graph indicates a normal distribution and random variation. The deviation data were found to be normally distributed, with a sample mean $\overline{X}$ of -0.7 watts per square meter and a sample variance of 24.8. The following equations apply:

$$\overline{X} = \frac{1}{n}\sum_{n} \delta p_2, \quad W/m^2 \tag{8a}$$

and

$$s^2 = \frac{1}{n-1}\sum_{n} (\delta p_2 - \overline{X})^2, \quad W^2/m^4 \tag{8b}$$

in which n is the number of bins, or 11 in this case.

In Table III, the data are listed on which Figure 6(b) is based. Deviations are first ranked from algebraically largest to smallest, and the number of bins exceeding a given deviation is calculated. One-half bin values result from the fact that the deviations given are median values for each bin. Probability of exceedance is then obtained by dividing each number in the third column in Table III by 11, the total number of bins in the sample.

In summary, statistical analysis of deviations from the PROP Code theory indicate the following:

1. Power density deviations from theory do not depend on power level, below 200 watts per square meter.

2. Sample mean deviation is -0.7 watt per square meter, with a variance of 24.8.

3. Correlation between experimental power output and theoretical power output is high.

Step 6: Estimation of Lower Bound on Mean Deviation from Theory

If a lower bound on the mean deviation from the power predicted using the PROP Code can be estimated with a high degree of confidence, then a guaranteed mean power can be established. A lower bound of this type can be calculated by conventional statistical methods from a sample mean $\overline{X}$ and a sample variance s^2. The applicable equation (ref. 11, for example) is as follows:

$$\mu(1-\alpha) \geq \overline{X} - t(1-\alpha, n-1)\sqrt{\frac{s^2}{n}}, \quad W/m^2 \tag{9}$$

in which μ is the actual, but unknown, mean deviation, $(1-\alpha)$ is the confidence level desired, and t is Student's factor which is tabulated in statistical references.

The level of confidence which should be used is a matter of judgment at this time. It should be high, to support a guarantee. For guidance, guaranteed minimum material properties usually imply a confidence level of 0.999. With this as a precedent, a confidence level of 0.999 was assumed for this study. Student's t-factor is 4.144 for a confidence level of 0.999 and a sample size of 11 units, which in this case are bins. Thus,

$$\mu(0.999) \geq -0.7 - 4.144\sqrt{\frac{24.8}{11}}$$

or

$$\mu(0.999) \geq -7 \text{ W/m}^2 \text{ (test conditions)} \quad 10(a)$$

A density correction is required to convert from test conditions to sea-level standard conditions, giving

$$\mu(0.999) \geq -8 \text{ W/m}^2 \text{ (standard conditions)} \quad 10(b)$$

Step 7: Analysis of Power-Train Losses

A general equation for power-train losses is needed before system output power can be calculated. The density of power-train losses, in watts per square meter, is listed for each bin in the last column of Table II and was calculated as follows:

$$p_{32} = \frac{1}{A}(P_3 - Q_3\Omega_2), \quad \text{W/m}^2 \quad (11)$$

Because of a calibration error in the electrical metering equipment, a zero correction to the output power data is needed. The following procedure was used to make this correction: As shown in Figure 7, the power loss data without the zero correction were plotted versus turbine power density p_2, to obtain a slope of -0.050 and an apparent zero-loss at zero power density. The actual loss at zero power density was obtained during a run-in test of a similar unit (without blades) by measuring the power consumed by the auxiliary drive motor (Table I). This power was approximately 11 kilowatts, indicating a loss of -10 watts per square meter in the power train under zero load. Thus, the power-train loss equation for the Mod-OA machine becomes

$$p_{32} = -10 - 0.050\, p_2, \quad \text{W/m}^2 \quad (12)$$

The zero correction to the output power data is therefore -11 kilowatts or -10 watts per square meter. Corrected output power densities are given in the third column of Table IV for each bin of test data, calculated using the equation

$$p_3 = \frac{P_3}{A} - 10, \quad \text{W/m}^2 \quad (13)$$

Experimental system efficiences are listed in the fourth column, calculated as follows:

$$\eta_3 = p_3/p_0 \quad (14)$$

The last column in Table IV gives the corrected output power data reduced to sea level standard conditions.

Step 8: Calculation of Guaranteed Mean Power Output

Guaranteed mean turbine power and guaranteed mean system power can now be calculated, using the lower-bound estimate on the mean deviation from theory, and the power-train loss equation. Results are listed in Table V. All calculations were made for sea-level standard conditions, with an air density of 1.225 kilograms per cubic meter.

First, the power density of the free-stream wind is calculated for wind speeds at convenient increments of 0.5 and 1.0 meter per second, using Equation (2). Next, theoretical turbine performance at these same wind speeds is calculated by means of the PROP Code and Equations (3) and (4). Results are listed in the third, fourth, and fifth columns of Table V.

Guaranteed mean turbine power density (column 6) is then calculated from the theoretical power density by adding the estimated lower bound on the mean deviation from Equation 10(b). Thus

$$p_{2,gm} = p_{2,th} - 8, \quad \text{W/m}^2 \quad (15)$$

The confidence level on the guaranteed mean power is assumed to remain at 0.999, the assumed confidence level used in estimating the lower bound on the mean deviation. Guaranteed mean turbine efficiency values are listed in the seventh column, as calculated using Equation (6).

Guaranteed mean generator power data are tabulated in the last three columns of Table V. Equation (12) has been applied as follows:

$$p_{3,gm} = 0.950\, p_{2,gm} - 10, \quad \text{W/m}^2 \quad (16)$$

Guaranteed mean system efficiency and generator output power are then easily calculated.

Figures 8, 9, and 10 show the data from Tables IV and V in graphical form. In Figure 8, turbine efficiencies are plotted versus tip-speed ratio. Guaranteed mean turbine efficiency peaks at 0.377, compared with a theoretical peak of 0.403. Figure 9 shows the variation of system output power with free-field wind speed, which is the format of most use to wind power system engineers. Guaranteed mean power and theoretical power curves are separated laterally by 0.3 meter per second at cut-in wind speed and less than 0.2 meter per second at rated. Vertically, separation is a constant 9 kilowatts or 8 watts per square meter. This is less than 5% of rated power and does not appear to be excessive, considering the high confidence level of 0.999.

Test data are also plotted on Figure 9 for comparison with both theoretical and guaranteed mean curves. Note that the data points at 47 kW and 69 kW fall below the solid curve, emphasizing that it is not a guaranteed minimum curve.

In Figure 10, the same system output data are displayed in terms of system efficiency versus free-field wind speed. This type of plot may be useful for selecting one or two points at which to guarantee system power output.

CONCLUSIONS

A method of calculating the guaranteed mean power output of a wind turbine generator has been described. The steps in the calculation procedure have been illustrated with data from the DOE/NASA Mod-OA 200 kW wind power plant in Clayton, New Mexico. On the basis of this analysis of performance test data, the following conclusions are drawn:

1. The PROP Code is a practical analytical tool with which the power from a wind turbine like the Mod-OA can be accurately predicted.

2. Deviations between measured and theoretical power do not appear to depend on power density up to 200 watts per square meter, and their distribution is random.

3. Subtracting 8 watts per square meter (9 kW) from the theoretical power output of the Mod-OA system gives a guaranteed mean power with a high degree of confidence.

4. Standard statistical analysis techniques and the method of bins are adequate for the calculation of guaranteed mean power from theory and test data.

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TABLE I

Performance Test Data From The
Clayton Mod-OA 200 kW Wind Turbine Generator
(Medians of Binned Data)

Bin no.	Turbine input wind V_1 m/s	Turbine shaft torque Q_2 N-m	Turbine shaft speed Ω_2 rad/s	Generator output power P_3 kW
(a) Record No. 1 (10 Jan 78, 2.2 hr on-line, air density = 1.104 kg/m^3)				
1	4.6	15,600	4.19	60
2	5.4	17,600	4.19	73
3	6.3	25,100	4.20	100
4	7.3	33,200	4.21	130
5	8.3	42,000	4.22	170
6	9.3	46,800	4.22	190
7	10.3	47,500	4.22	190
(b) Record No. 2 (18 Jan 78, 4.6 hr on-line, air density = 1.098 kg/m^3)				
8	3.7	12,200	4.19	45
9	4.6	13,600	4.19	54
10	5.6	21,700	4.20	84
11	6.5	27,100	4.20	110
12	7.5	35,200	4.21	140
13	8.5	42,000	4.22	170
14	9.5	46,100	4.22	180
15	10.5	47,500	4.22	190
(c) Shop Run-In (Dec 79, similar unit)				
--	---	0	4.19	-11 [a]

a Auxiliary drive motor on transmission output shaft

TABLE II

Results of Performance Tests on the Clayton Mod-OA 200 kW Wind Turbine Generator and Comparison with Theoretical Turbine Performance

Bin No.	Free-stream wind at turbine midline		Theoretical turbine output power (from PROP Code)			Turbine test results calculated from data in Table I			
	Speed V_0 m/s	Power density P_0 W/m²	Tip speed ratio λ	Turbine efficiency $\eta_{2,th}$	Power density $P_{2,th}$ W/m²	Power density P_2 W/m²	Turbine efficiency η_2	Deviation from theory δP_2 W/m²	Power train losses[a] P_{32} W/m²
1	6.46	148	12.3	0.390	58	58	0.39	0	-4
2	6.99	188	11.3	.400	75	65	.34	-10	0
3	7.59	241	10.5	.405	98	94	.39	-4	-5
4	8.26	310	9.63	.399	124	124	.40	0	-8
5	8.93	393	8.93	.389	153	158	.40	5	-6
6	9.59	486	8.32	.375	182	176	.36	- b	-7
7	10.26	595	7.77	.333	198	179	.30	- c	-10
8	5.86	111	13.5	.351	39	46	.41	7	-6
9	6.46	148	12.3	.390	58	51	.34	-7	-3
10	7.12	199	11.1	.403	80	81	.41	1	-6
11	7 73	254	10.3	.404	103	101	.40	-2	-3
12	8.39	325	9.48	.397	129	132	.41	3	-7
13	9.06	410	8.80	.387	159	158	.38	-1	-6
14	9.73	508	8.20	.371	188	174	.34	- b	-7
15	10.39	618	7.68	.320	198	179	.29	- c	-10

a Zero correction required; deduct 10 W/m²
b Not applicable; blades incorrectly pitched
c Not applicable; wind speed above rated

TABLE III

Probability Distribution of Deviations from Theoretical Turbine Power Density

Bin No.	Deviation from theory δP_2 W/m²	Number of bins exceeded	Probability of exceedance %
8	7	0.5	4.5
5	5	1.5	13.6
12	3	2.5	22.7
10	1	3.5	31.8
1	0	4.5	40.9
4	0	5.5	50.0
13	-1	6.5	59.1
11	-2	7.5	68.2
3	-4	8.5	77.3
9	-7	9.5	86.4
2	-10	10.5	95.5

Sample mean: $\overline{X} = -0.7$

Sample variance: $s^2 = 24.8$

TABLE IV

System Output Power and Efficiency Test Results for the Clayton 200 kW MOD-OA Wind Turbine Generator

Bin no.	Free-stream wind speed V_0 m/s	Output power density, test conditions P_3 W/m²	System efficiency η_3	Output power, sea-level standard conditions P_3 kW
1	6.46	44	0.30	55
2	6.99	55	.29	69
3	7.59	79	.33	99
4	8.26	106	.34	132
5	8.93	142	.36	177
6	9.59	159	---	---
7	10.26	159	---	---
8	5.86	30	.27	37
9	6.46	38	.26	47
10	7.12	65	.33	81
11	7.73	88	.35	110
12	8.39	115	.35	144
13	9.06	142	.35	177
14	9.73	157	---	---
15	10.39	159	---	---

TABLE V
Theoretical and Guaranteed Mean Power From a 200 kW Mod-OA Wind Turbine Generator, Under Sea-Level Standard Conditions

Free-stream wind at turbine midline		Theoretical turbine output power (from PROP Code)			Guaranteed mean power (0.999 conf. level)				
					Turbine output		Generator output		
Speed	Power density	Tip speed ratio	Turbine efficiency	Power density	Power density	Turbine efficiency	Power density	System efficiency	Power
V_0	P_0	λ	$\eta_{2,th}$	$P_{2,th}$	P_2	η_2	P_3	η_3	P_3
m/s	W/m^2			W/m^2	W/m^2		W/m^2		kW
4.0	39	19.8	0.038	1	-7	-0.179	-17	-0.436	-19
4.5	56	17.6	.161	9	1	0.018	-9	-0.161	-10
5.0	77	15.9	.247	19	11	.143	0	.000	0
5.5	102	14.4	.314	32	25	.245	14	.137	15
6.0	132	13.2	.364	48	40	.303	28	.212	32
6.5	168	12.2	.393	66	58	.345	45	.268	50
7.0	210	11.3	.402	84	76	.362	62	.295	70
7.5	258	10.6	.403	104	96	.372	81	.314	91
8.0	313	9.91	.402	126	118	.377	102	.326	114
8.5	376	9.33	.396	149	141	.375	124	.330	139
9.0	446	8.81	.388	173	165	.370	147	.330	165
9.5	525	8.35	.377	198	190	.362	170	.324	191
10.0	612	7.93	.324	↓	198	.324	178	.291	200
11.0	815	7.21	.243	↓	↓	.243	↓	.218	↓
12.0	1058	6.61	.187	↓	↓	.187	↓	.168	↓
13.0	1345	6.10	.147	↓	↓	.147	↓	.132	↓
14.0	1679	5.66	.118	↓	↓	.118	↓	.106	↓
15.0	2066	5.29	.096	↓	↓	.096	↓	.086	↓
16.0	2507	4.96	.079	↓	↓	.079	↓	.071	↓
17.0	3007	4.66	.066	↓	↓	.066	↓	.059	↓
18.0	3569	4.41	.055	↓	↓	.055	↓	.050	↓

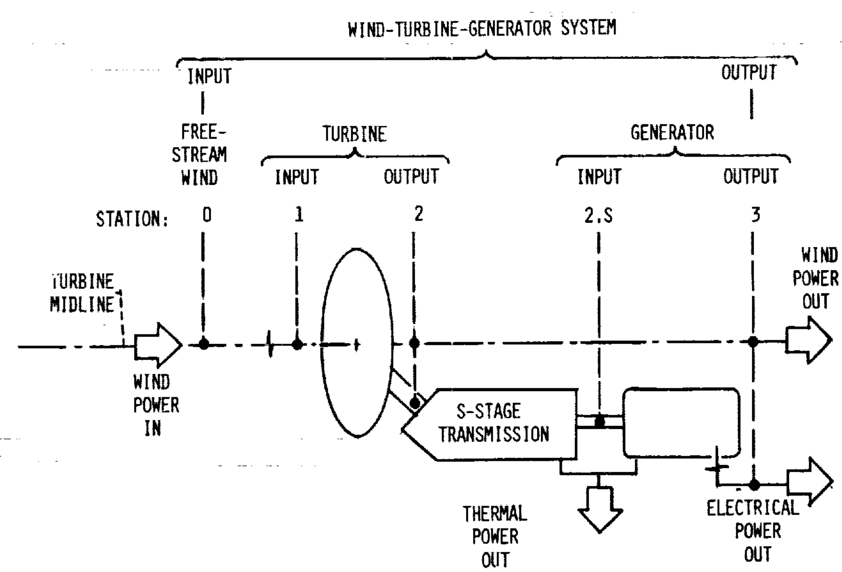


Figure 1. - Schematic diagram of a general wind turbine generator system, showing measuring stations and power flow.

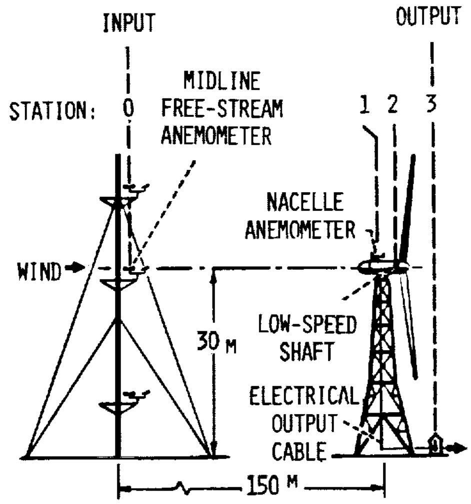


Figure 2. - Performance test installation at Clayton, New Mexico, showing the Mod-OA 200 kW wind turbine generator, the anemometer tower, and measurement stations.

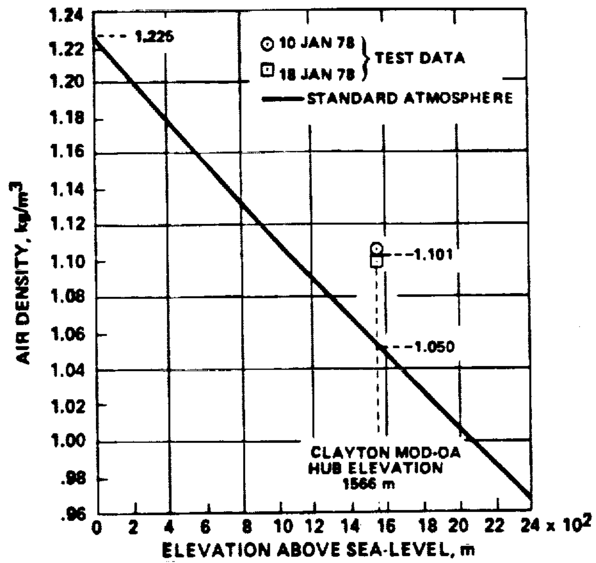


Figure 4. - Air densities during performance tests on the Clayton Mod-OA wind turbine, compared with Standard Atmosphere density.

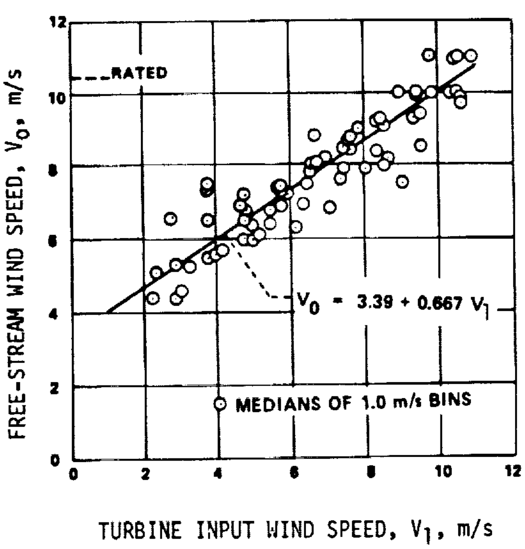


Figure 3. - Correlation of free-stream wind speed at hub height with turbine input wind speed, for the Clayton Mod-OA wind turbine.

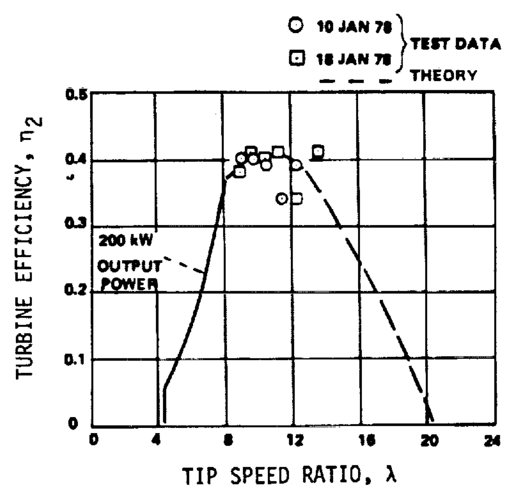
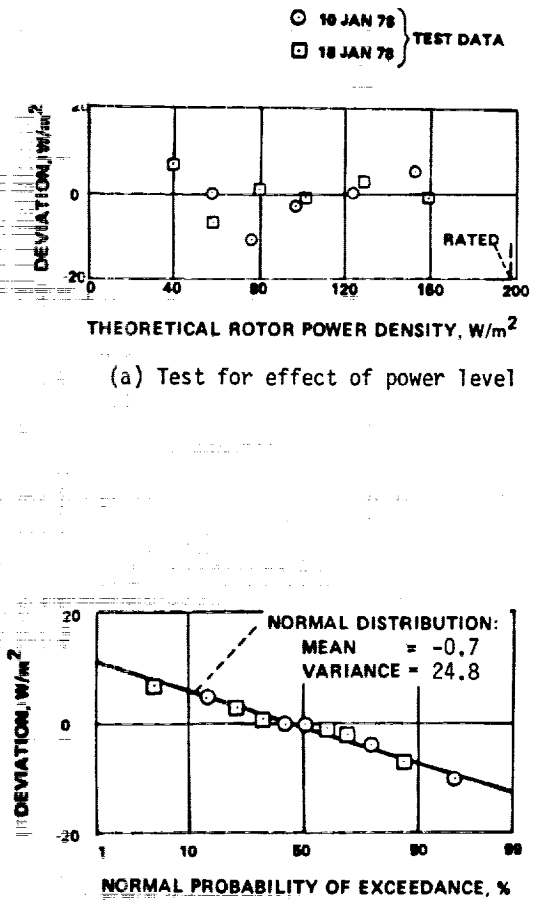


Figure 5. - Theoretical and experimental turbine efficiencies for the Mod-OA 200 kW wind energy system in Clayton, New Mexico.



(a) Test for effect of power level

(b) Test for normal distribution

Figure 6. - Deviation of measured turbine power density from theoretical power density, calculated using the PROP Code.

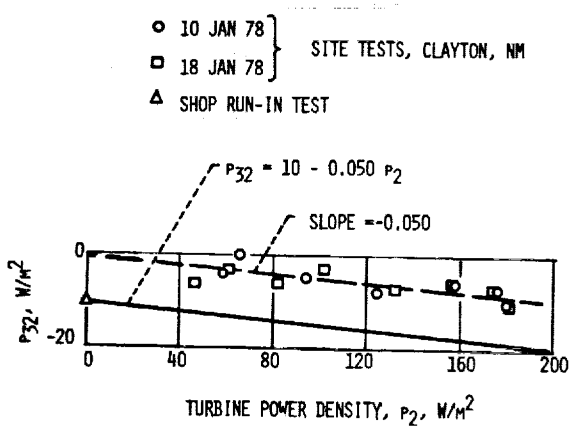


Figure 7. - Analysis of power-train losses in the Mod-OA 200 kW wind turbine system.

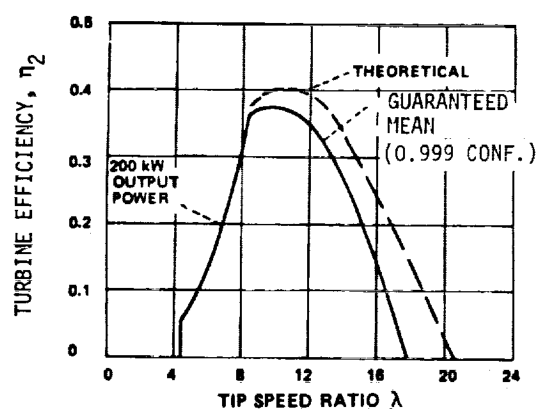


Figure 8. - Theoretical and guaranteed mean turbine efficiencies for the Mod-OA 200 kW wind energy system.

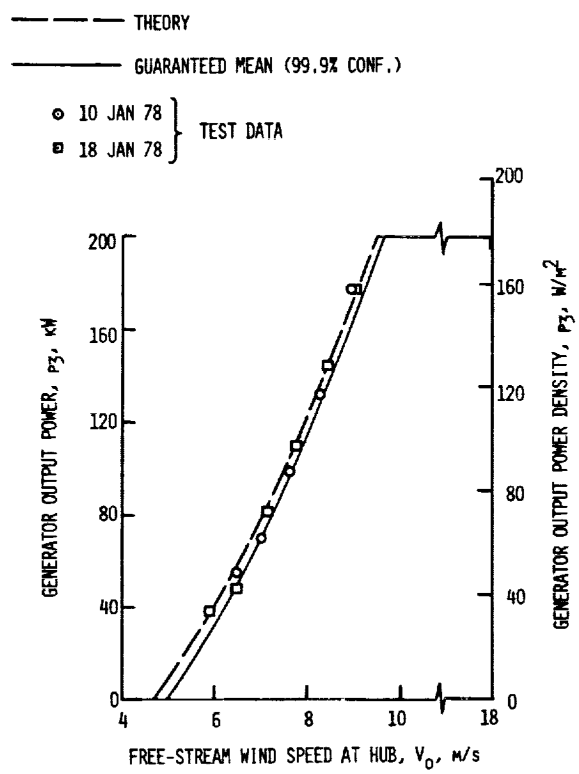


Figure 9. - Generator output power of the Mod-OA 200 kW wind energy system under sea-level standard conditions.

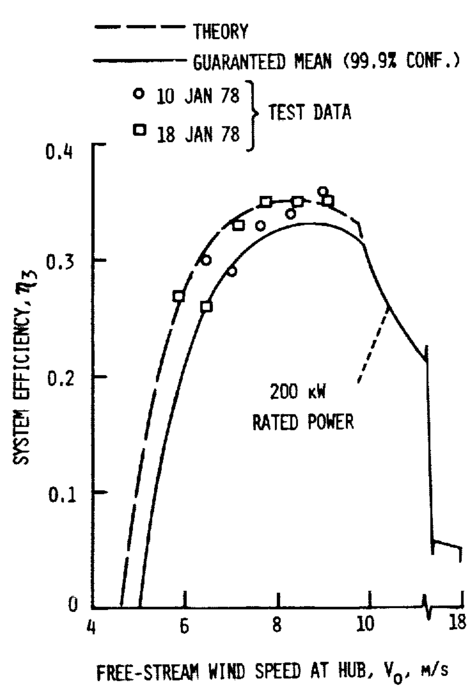


Figure 10. - Overall efficiency of the Mod-OA 200 kW wind energy system.