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DOE/NASA MOD-OA WIND TURBINE PERFORMANCE

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NOTICE

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ABSTRACT

As part of the national wind energy program under the direction of the Department of Energy, the NASA-Lewis Research Center has designed and built, and is now operating, a large wind turbine at Clayton, New Mexico. Designated the Mod-0A-1, this is the first of three identical 200 kW wind turbines to be operated on electric utility networks. This machine was installed at Clayton, New Mexico, in November 1977. This paper presents a comparison between its predicted and measured power versus wind speed performance.

BACKGROUND - As part of the Federal wind energy program under the direction of the Department of Energy, the NASA-Lewis Research Center (LeRC) is responsible for developing large, horizontal-axis wind turbines. Current projects at LeRC include turbine designs with rotor diameters ranging from 125 to 300 feet and generating capacities from 100 to 2500 kW.

The first of these designs to be built, the Mod-0 wind turbine (1),* consists of a two-bladed, 125-foot diameter rotor which drives a 100-kW capacity synchronous alternator through a step-up gearbox. This machine was built to provide early engineering data on the operation of large wind turbines and to serve as a testbed for various subsystems and components which held promise for reducing costs and increasing the reliability of later wind turbine designs.

The second of these designs, the Mod-0A wind turbine system, was derived directly from the Mod-0 design, with three minor modifications: stronger and heavier blades, an all-pipe truss tower as opposed to the Mod-0's pipe-and-channel tower design, and a larger capacity alternator and drivetrain. Although nearly identical in design to Mod-0, the Mod-0A machines are being built and tested for a different purpose; obtaining early operation and performance data and gaining experience while operating in typical utility environments (2). As such, the Mod-0A design was not developed under the stringent cost goals and constraints to which current designs are being subjected (3,4).

Of primary importance in the design of any wind turbine is the accurate prediction of energy output as a function of site wind characteristics. This prediction involves the combining of site wind duration curves and the power-versus-wind speed performance of the wind turbine. The wind turbine's performance is determined by the product of two efficiencies: the aerodynamic efficiency of the rotor in converting from wind power to shaft power and the mechanical/electrical efficiency of the drivetrain/alternator system in converting shaft power to electrical power. This paper presents a comparison of predicted and measured performance for the Mod-0A wind turbine.

MOD-0A DESCRIPTION

The Mod-0A wind turbine has a 125-foot diameter, two-bladed rotor which drives a 200-kW capacity synchronous generator through a step-up gearbox. The rotor is positioned downwind of a 100-foot steel-truss tower, as pictured in Fig. 1. The rotor is designed to operate at a constant speed of 40 rpm and it drives a 60 Hz three-phase alternator at 1800 rpm. Constant rotor speed is maintained by controlling the blade pitch angle with a feedback control system. The rotor, alternator, transmission, and associated equipment are mounted on a bedplate, which is yawed to align the rotor with the wind. Power, instrumentation, and control connections to the ground are made through slip rings.

The Mod-0A wind turbine in Clayton, New Mexico, achieved first rotation in November 1977. Data reported here was recorded during the initial checkout phase of the Clayton installation, and corresponds to the normal operating mode of the Mod-0A wind turbine: synchronized to the utility network and utilizing a power feedback control loop for blade pitch control. The control system consists of integral control on power and feed-forward on wind speed. This control scheme is described in detail in Ref. 1.

COMPARISON OF PREDICTED AND ACTUAL PERFORMANCE

PREDICTIONS - The performance predictions for the Mod-0A wind turbine were calculated using an aerodynamic performance code PROP (5). This analysis is based on the blade element/momentum theory of rotor performance. Details of the Mod-0A blade geometry are given in Ref. 6, and the airfoil data used were NASA roughness. NASA roughness is defined as halfway between the smooth and standard roughness data found in Ref. 7.

DATA SYSTEM AND SITE LAYOUT - The data system used for recording Mod-0A performance data consists of approximately 85 measurement sensors,

*Numbers in parentheses designate References at end of paper.

three multiplexing devices, analog-to-digital converters, and recording of the data in both analog and digital form. The parameters recorded for determining performance are: alternator power output, meteorological tower wind speed at 100 feet, nacelle wind speed, and rotor shaft torque. The general layout of these sensors is shown in Fig. 2. The nacelle anemometer is located approximately 15 feet upwind of the plane of the rotor and 9 feet above the rotor centerline. The meteorological tower is located 500 feet from the wind turbine, and was upwind of the wind turbine when the data reported here were recorded.

MEASURED POWER VERSUS WIND SPEED - The process of correlating wind turbine performance with wind measurements is not completely straightforward. Two problems are encountered in making the correlation. First, wind measurements must be made close enough to the wind turbine to be representative of the "same" wind that drives the rotor, but far enough away to eliminate any interference effects. Second, an anemometer registers a wind value at a point, while the turbine responds to the wind that engulfs the entire disk swept by the blade.

The approach taken here to eliminate these problems is: (1) to provide a wind measurement as close to the rotor as possible, the average alternator power for each revolution of the rotor was correlated with the simultaneous measurement of nacelle wind speed. Figure 3 shows a sampling (1/20th) of the 1½ hours of data analyzed for this paper. (2) To eliminate the interference effects of the rotor and nacelle on the nacelle wind measurements, the 2-minute averages of wind speeds at the nacelle and meteorological tower at 100 feet are related. This is done by calculating the least squares best-fit straight line to the data. Two-minute averaging was chosen based on (unpublished) calculations of spectral content of the wind and results reported elsewhere (8). This data and the curve fit are shown in Fig. 4. Then, the wind measurements in the power-versus-nacelle wind relation are rescaled, using the equation of this best-fit line. The final result of alternator power versus free-stream wind speed is shown in Figs. 5(a) and (b).

The data shown in Figs. 5(a) and (b) are explained as follows: the upper portion of the figure shows the statistics of groups of the measured parameters - where the data are grouped into wind speed intervals of 3 mph each. The symbols depicting the statistics of each group are defined as: the top bar on each symbol represents the upper bound of 84 percent of the data in the group, two symbols (squares) indicate the 90 percent confidence interval about the mean, and the lower dash represents the upper bound of the 16th percentile. This method of reducing data scatter for comparisons with theory and Sandia's "method of bins" (9) share some common features, although this method retains more information. Both methods are applications of standard data analysis techniques (10). Figure 5(b) shows the total number of data values analyzed, as well as the percentage of this total included in each group.

The comparison in Fig. 5(a) shows general agreement between the theory (shown as the solid line) and measured performance of the Mod-0A wind turbine. The deviation from theory (based on steady-state winds) near rated wind speed, that is, at the "sharp corner" of the curve, is well understood and has been discussed fully by Golding (11). It is due to the fluctuation of the wind about its "steady" value which is equivalent to the wind turbine retaining an averaging on the two sides of the "corner." To account for this smoothing, the corner of the theoretical curve can be rounded, as shown in Fig. 5(a).

CONCLUSIONS

Of primary importance in the design of any wind turbine is the accurate prediction of the machine's performance characteristics. This paper compares the predicted power-versus-wind speed performance of the Mod-0A wind turbine with predictions made using the PROP code. This comparison demonstrates that the Mod-0A wind turbine has power-versus-wind speed performance which closely matches predictions. Also, the method discussed here for processing the measured data is a valuable tool which enables design analyses to be verified by field measurements.

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Fig. 1 - Mod-OA

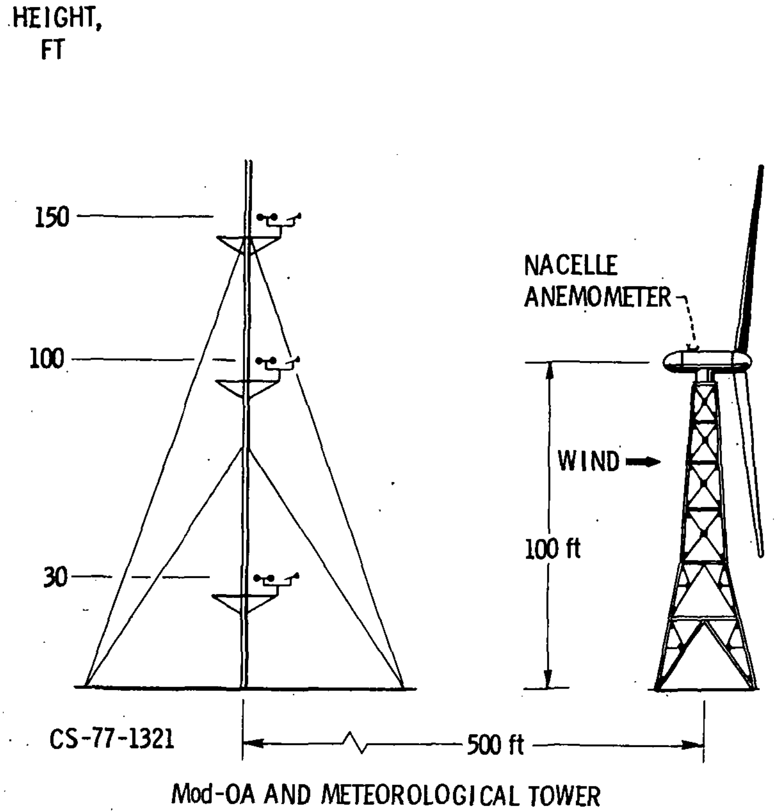

Fig. 2 - Wind turbine and meteorological tower configuration

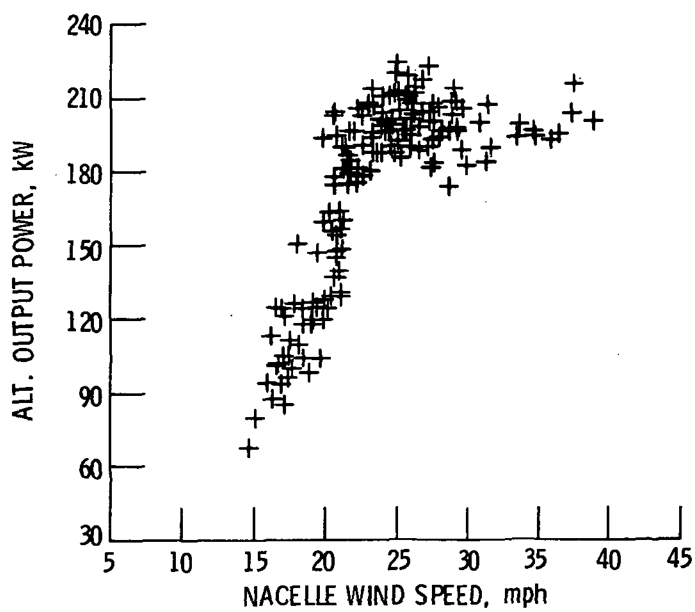

Fig. 3 - Alternator power output vs wind speed measured on the nacelle. Each point represents simultaneous 1-revolution (1.5 sec) averages

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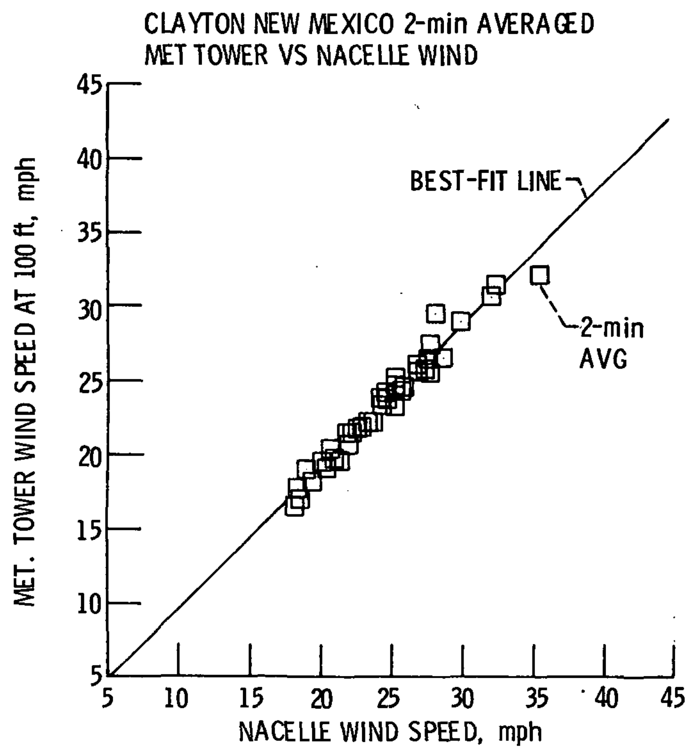
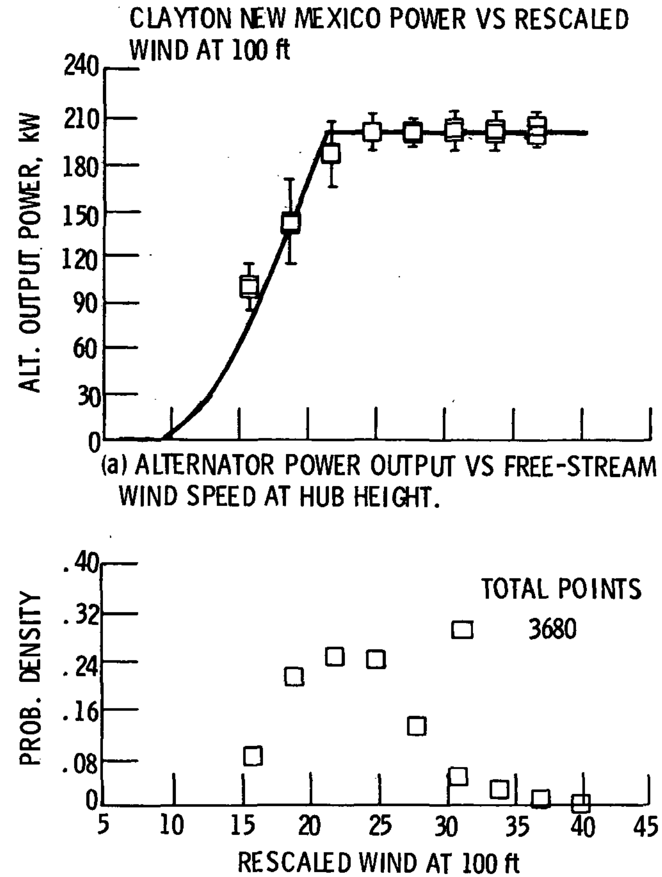


Fig. 4 - Simultaneous two-minute averages of meteorological tower wind speed at 100 feet vs nacelle wind speed. The line is the least squares best-fit line to the data



(a) ALTERNATOR POWER OUTPUT VS FREE-STREAM WIND SPEED AT HUB HEIGHT.

(b) HISTOGRAM OF WINDS FOR DATA SHOWN IN FIGURE 5(a).

Fig. 5

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