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Vertical Axis Wind Turbine Control Strategy

Gerald M. McNerney

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Vertical Axis Wind Turbine Control Strategy

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Abstract

Algorithm control strategy for unattended wind turbine operation at the low wind speed cut-in condition is a potentially important aspect of wind energy production that has thus far not been fully treated in the literature. Early experience in automatic operation of the Sandia 17-m vertical axis research wind turbine (VAWT) has demonstrated the need for a systematic study of control algorithms. To this end, a computer model has been developed that uses actual wind time series and turbine performance data to calculate the power produced by the Sandia 17-m VAWT operating in automatic control. The model has been used to investigate the influence of starting algorithms on annual energy production. The results indicate that, depending on turbine and local wind characteristics, a bad choice of a control algorithm can significantly reduce overall energy production. The model can be used to select control algorithms and threshold parameters that maximize long-term energy production. An attempt has been made to generalize these results from local site and turbine characteristics to obtain general guidelines for control algorithm design.

Acknowledgment

The author extends his appreciation to M. T. Mattison Division 4715, for his help in initiating this study and to W. N. Sullivan, also of Division 4715, for his continued support and helpful ideas in carrying out the necessary work.

Vertical Axis Wind Turbine Control Strategy

Introduction

We have developed a computer model that uses test data to calculate the energy produced by a vertical axis wind turbine (VAWT) running on automatic control. The purpose of the model is twofold:

- To develop guidelines in control algorithm strategies. This task was initially undertaken by using data specific to the Sandia/DOE VAWT and it produced interesting results that could be applied to the automatic control program.
- To provide general information on the percentage of energy available to a VAWT that is lost in the automatic control process. This information will be used to select economical VAWTS for specfic sites.

I will discuss the automatic control model, followed by the algorithms tested and their results, and finally, generalized information that will apply to other turbine-site pairs.*

The Computer Model

The computer model was designed to simulate the Sandia/DOE 17-m Research VAWT at Albuquerque, NM, running on automatic control. Two sets of data are needed to simulate a turbine-site pair:

- A turbine electric power curve (EPC) that presents the turbine's power output as a function of windspeed
- A windspeed-time series at a sampling frequency of at least 0.1 Hz

The EPC data is a set of Bins data collected at the Sandia test site from the 17-m VAWT, operating at 5.3 rad/s.[1] Figure 1 plots these data. The windspeed-time series data were collected in 43 recording periods totalling 890 hours (at a frequency of 0.5 Hz) during weekends and nights of the summer and fall of 1979. The probability density function of the windspeed is plotted in Figure 2. The mean value of windspeed for the data is 4.96 m/s, which is above the actual Albuquerque mean annual windspeed, thereby reflecting a bias toward high wind.

The computer model itself is a FORTRAN program in which the electric power, as a function of windspeed data, is used to determine the power available at each sampling event. If the turbine is stopped, the control algorithm uses the power available to decide if the turbine should be started. If the turbine is running, the power is summed to determine the energy generated. (I will be discussing portions of the more interesting control algorithms in FORTRAN logic later in this report.)

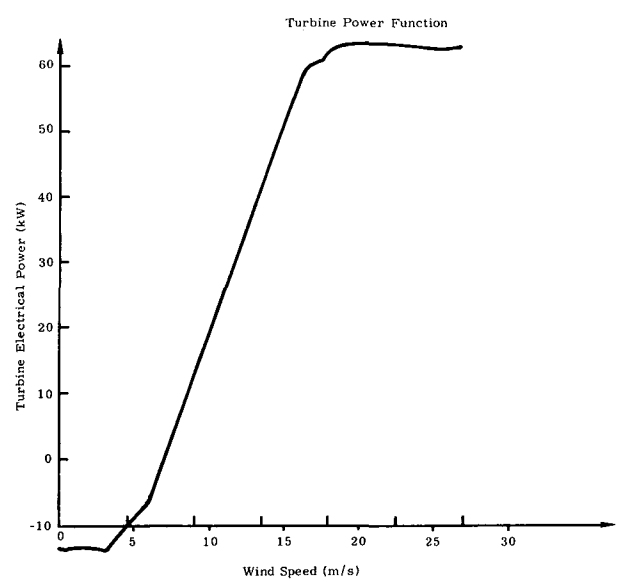


Figure 1. Bins Data for 17-m VAWT

*A turbine-site pair refers to a site and a turbine considered as a unit; some turbines may not be compatible with a particular site, but only by combining the specifications for both can compatibility be determined.

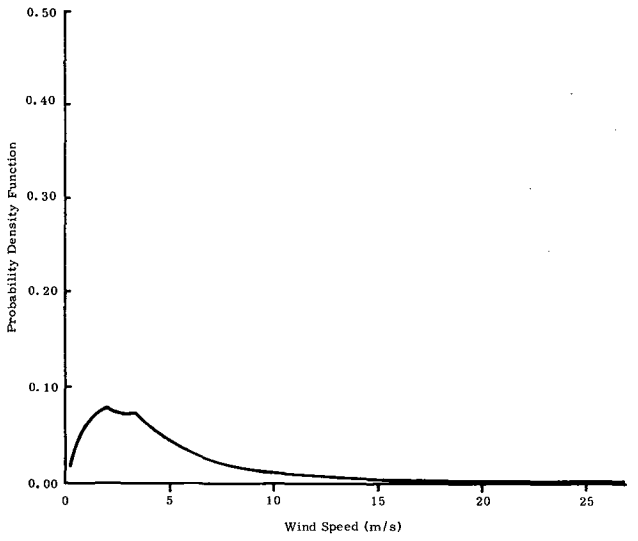


Figure 2. Probability Density Function of Windspeed

The overall energy output that is computed for a particular control algorithm depends on when and how long the turbine runs, as well as the number of starts. The energy consumed by each start is added up, and that sum is subtracted from the calculated energy produced when the turbine is running. For the Sandia/DOE 17-m VAWT, each start consumes approximately 0.6 kWh.

The output of the automatic control simulator is given as an algorithm efficiency as well as by the number of starts occurring over the duration of the wind data. The notion of algorithm efficiency* will be given precise meaning following the preliminary notion of the energy available to a turbine-site pair.

Energy Available

The energy available to a turbine-site pair over the time period, T, is calculated as follows:

$$E_T = T \int_{v_o}^{cs} \text{power}(v) \cdot p(v)\, dv\,, \qquad (1)$$

where power (v) is the turbine EPC or the average power produced by the turbine at windspeed, v; p(v) is the windspeed probability density function (PDF) over the time interval, T; and v_o is the cut-in windspeed.

Power (v) < 0 for $v < v_o$, and
Power (v) ≥ 0 for $v \geq v_o$.

*The algorithm efficiency of an automatic control system for a turbine-site pair over a test period is that proportion of energy produced by the turbine-site pair, operating under algorithm control, to that of the energy available over the test period.

In practice, the EPC and the PDF for an actual turbine and site are given as a finite set of values, in which case

$$E_T = T \cdot \sum_{\text{Power}>o} \text{Power}(v_i) \cdot p(v_i). \qquad (2)$$

The energy available then represents the ideal maximum energy that could be produced by a turbine-site pair.

Algorithms Tested

Five different algorithms have been tested by the automatic control simulator in parameter studies:

- Discrete windspeed
- Moving windspeed
- Moving power
- Discrete, double-power
- Canadian coasting

The first four have two parameters that are adjusted to find the optimum operating values:

- Cut-in/cut-off threshold — The minimum value of average windspeed or average power that is required to start or stop a turbine at low windspeed by a decision loop of a control algorithm
- Test window — The duration of the test period over which the average windspeed or power is calculated for comparison with the cut-in/cut-off threshold

Discrete Windspeed Algorithm

A windspeed average is calculated and tested against the cut-in/-off threshold at the end of each test window. If the turbine is parked and the average is greater than the cut-in threshold, the turbine is started. If the turbine is operating and the average is less than the cut-off threshold, the turbine is stopped.

Moving Windspeed Algorithm

A windspeed average is calculated and tested against the cut-in/-off threshold over the test window after each windspeed reading. After a start or stop, a 60-second blind period is introduced to simulate an actual start or stop. The cut-in algorithm actually used follows:

Initially, IC1 = 1,
T = test window
NPT = number of sample points in T

CIT = cut in threshold
WSSUM = 0
ARRAY (I) = 0, I = 1, NPT
WSR = current windspeed reading

with these values,

```
    START
10  READ WSR
    IC = IC1
    IC1 = IC1 + 1
    IF (IC1.GT.NPT) IC1 = 1
    WSSUM = WSSUM + WSR
    WSAUG = WSSUM/T
    WSSUM = WSSUM - ARRAY (IC1)
    ARRAY (IC) = WSR
    IF (WSAUG.GE.CIT) START
    Continue to 10.
```

Moving Power Algorithm

The average power is calculated from the power-as-a-function-of-windspeed table of the EPC and tested against the cut-in/-off threshold over the test window after each windspeed reading. After a start or stop, a 60-second blind period is introduced to simulate an actual start or stop. The cut-in algorithm actually used follows:

Initially, IC1 = 1
T = test window
NPT = number of sample points in T
CIT = cut in threshold
PSUM = 0
ARRAY (I) = 0 I = 1, NPT
IWS = integer nearest the current windspeed ready
Δt = sample period

with these values,

```
    START
10  READ IWS
    PR = POWER (IWS) *Δt
    IC = IC1
    IC1 = IC1 + 1
    IF (IC1.GT.NPT) IC1 = 1
    PSUM = PSUM + PR
    PAUG = PSUM/T
    PSUM = PSUM - ARRAY (IC1)
    ARRAY (IC) = PR
    IF (PAUG.GE.CIT) START
    Continue to 10.
```

Discrete, Double Power Algorithm

At the end of each test length, two power averages are calculated, one for the average over the entire test window and the other for the last one-tenth of the test window. For a start to occur both values must be greater than the cut-in threshold. Stops are based on a test of the average power over the entire test window.

Canadian Coasting Algorithm

Certain Canadian VAWT systems have used a semi-mechanical control system with an overruning clutch on the high-speed shaft to permit the rotor to coast when it is turning below the synchronous speed. This system simplifies the cut-off condition-to-rad/s measurements, and could conceivably reduce motoring losses in low winds.

From a cold stop, an algorithm other than the Canadian coasting one is used to decide if a start should be initiated by a motor that takes the turbine to some fraction of the synchronous rotational speed. The turbine is then allowed to coast either until synchronous speed is reached, at which time the generator engages, or until 5 minutes have elapsed and the turbine falls below a cut-off threshold rotational speed. If syncronization is reached, when torque at the high-speed shaft later becomes negative, the generator disengages and the turbin begins coasting again. Whenever the rotor is coasting, the generator is assumed to motor without shaft load at synchronous speed. Windage losses in the generator are accumulated during coasting periods. The only parameter is the cut-off threshold rotational speed.

The turbine rotational speed during free coasting in a varying windspeed is given by the differential equation

$$\frac{dw}{dt} = \frac{T_A - T_f}{I},$$

where

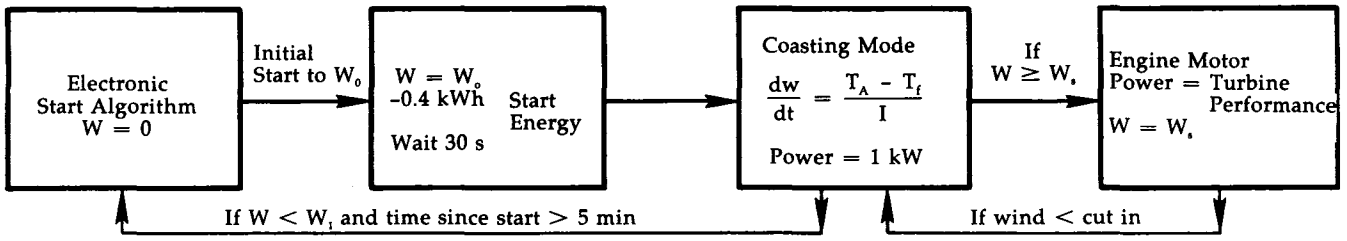
w = rotational speed
T_f = rotor friction torque
I = rotor inertia
T_A = aerodynamic torque as a function of windspeed:

$$T_A = \frac{1}{2}\rho A V^3 \left[\frac{RW}{V}\right]^3 K_p(v)$$

$K_p(v)$ = power coefficient tabulated from 17-m Bins data.

We assume that, the K_p, when plotted against the windspeed data, does not vary with rotational speed, which is accurate over the small range of rotational speeds of interest.

Figure 3 is the logic flow chart used to simulate the turbine rad/s and energy output.



Notes: W_0 = initial rotor rotational speed
W_s = syncronus rotor rotational speed
W_1 = cut-off threshold rotational speed
W = current rotational speed

Figure 3. Logic Flow Chart; Turbine Rad/s and Energy Output

Results of Parameter Studies

The results of the computer runs for parameters of the five algorithms are plotted in Figures 4 through 8. The maximum curves from each algorithm are then plotted together for easy comparison (Figure 9). The following points become evident from the figures:

- For each algorithm, parameters can be chosen that maximize the algorithm's efficiency and miminize its coasting time and number of starts
- The algorithms can be ranked in the order of their maximum efficiency:
  -Canadian coasting: 93.7%
  -moving power: 93.4%
  -discrete, double-power: 92.8%
  -discrete windspeed: 92.3%
  -moving windspeed: 91.6%
- Badly chosen parameters, particularly the test window, greatly reduce the efficiency of an algorithm

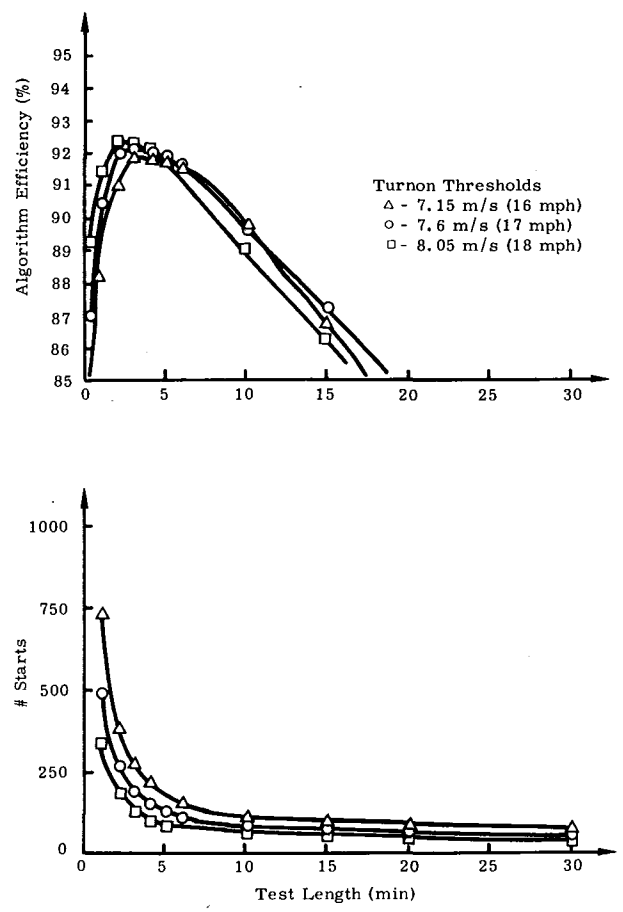


Figure 4. Algorithm #1 - Discrete Windspeed Averages and Number of Starts

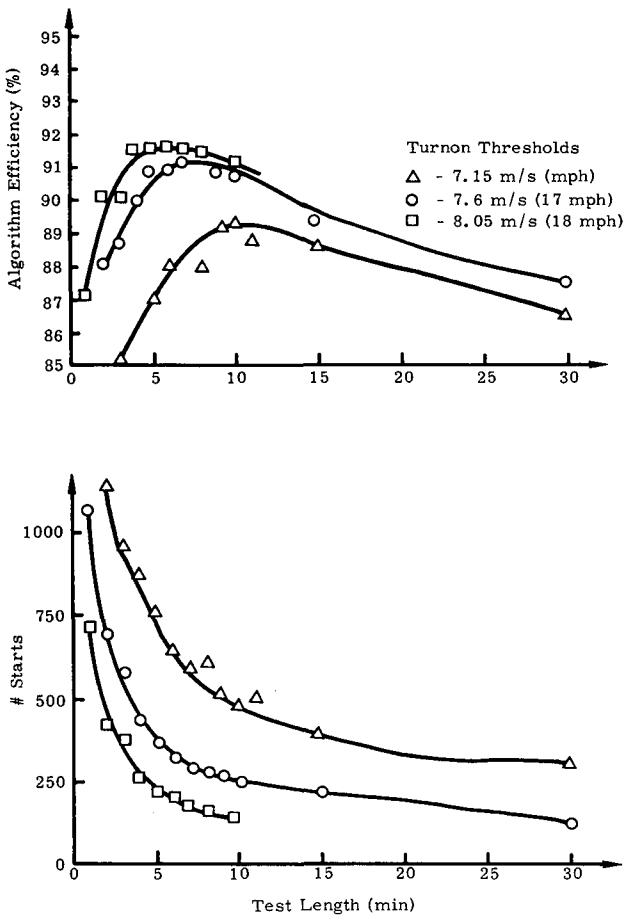


Figure 5. Algorithm #2 - Moving Windspeed Averages and Number of Starts

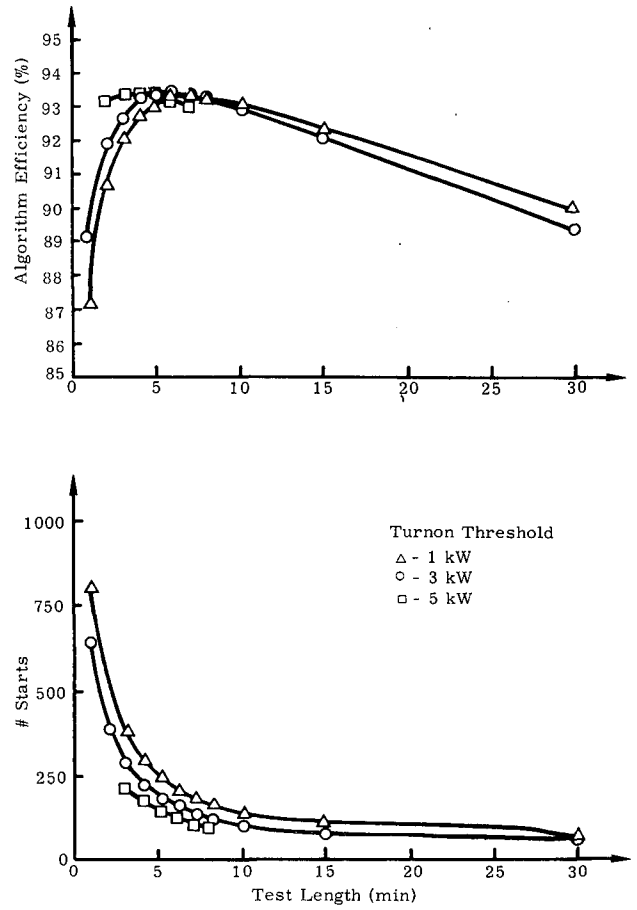


Figure 6. Algorithm #3 - Moving Power Averages and Number of Starts

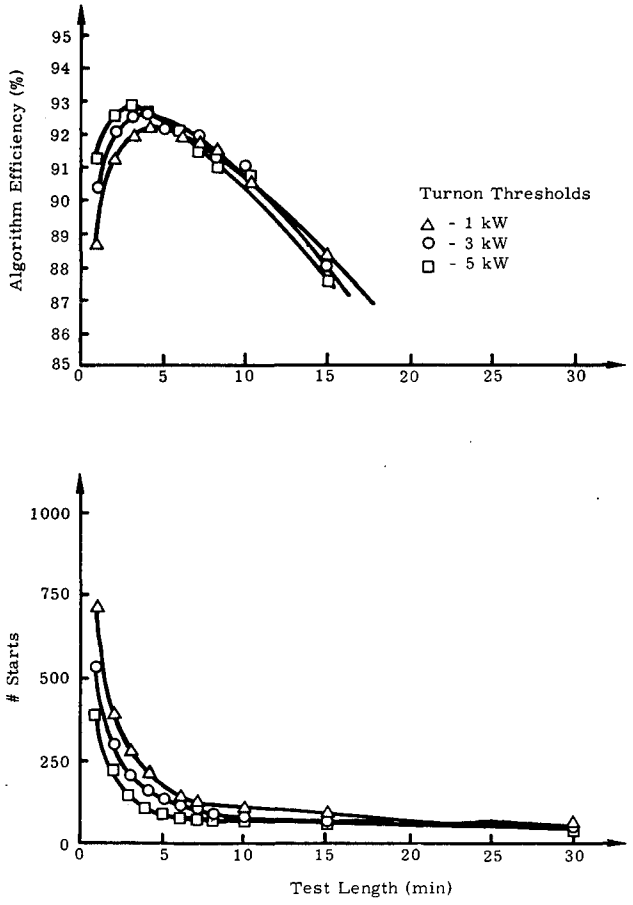


Figure 7. Algorithm #4 - Discrete, Double Power Test and Number of Starts

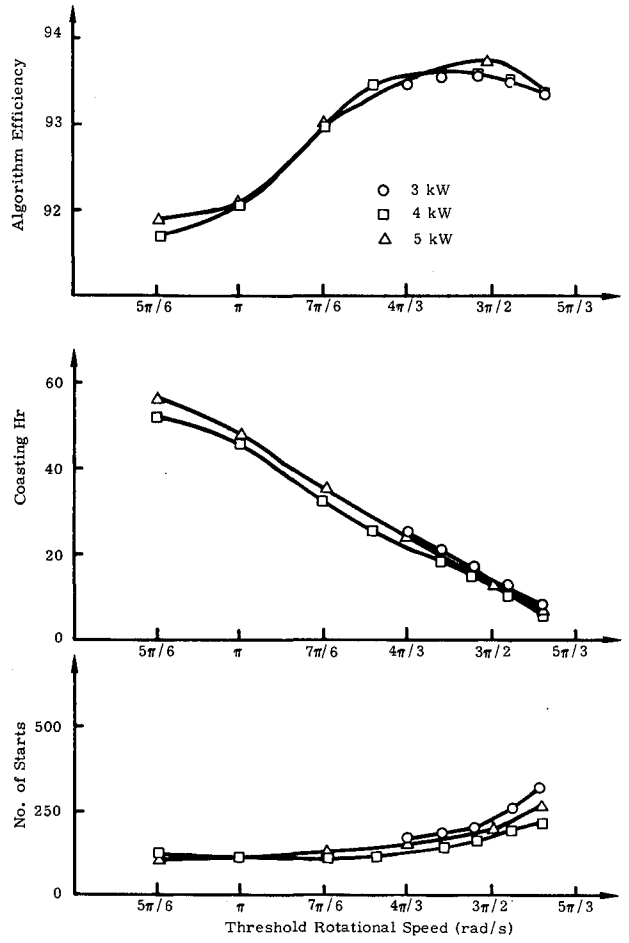


Figure 8. Canadian Coasting Algorithm, Duration of Coasting, and Number of Starts

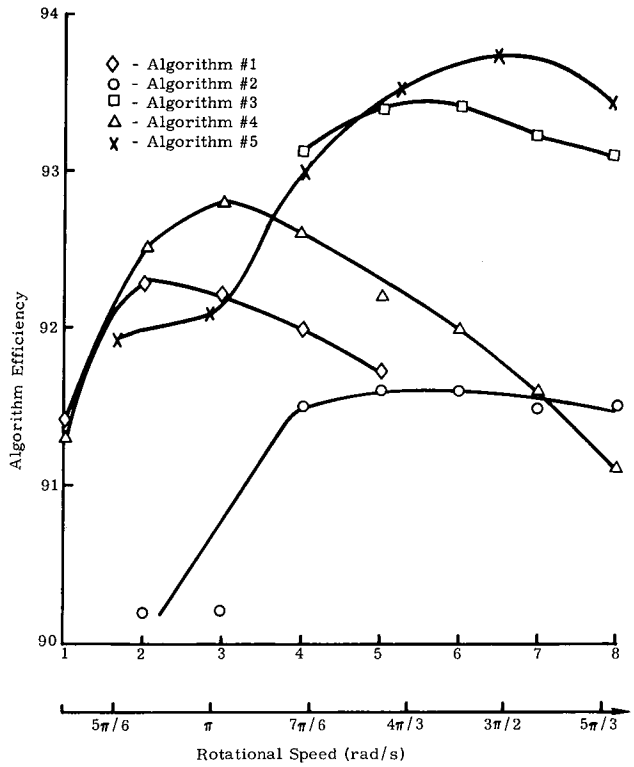


Figure 9. Comparison of the Best Curves of the Five Algorithms

Applications to VAWT Economics

The study on algorithm control can be used to maximize energy production, once a particular turbine-site pair has been selected. However, if a turbine is badly matched to a site, the maximum efficiency of an algorithm may be as low as 72%. Therefore, control algorithms can affect the economics of wind energy production.

To use control algorithms in wind energy economics, we must determine if the maximum efficiency depends on the probability distribution function (PDF) of local windspeed suitably combined with the turbine EPC. Since the PDF and the EPC are functions of windspeed, it is natural to use both to construct the energy distribution function (EDF) which, at any windspeed, gives the fraction of the annual energy produced by the machine at that particular windspeed. Since the EDF is the product of the PDF and the EPC, we should concentrate on determining how much the maximum algorithm efficiency depends on the EDF.

The first time the five algorithms were tested, we used the EPC from the Sandia/DOE 17-m VAWT (determined from experiments based on the Bins method) and the windspeed time series recorded at the same test site. We could find no general relationship between the maximum algorithm efficiency and the EDF in the data from only one turbine-site pair. Therefore, we expanded the data base to include several more turbine EPCs and another set of windspeed time series that consisted of data recorded from October 1, 1976 to November 26, 1977 by the National Severe Storm Laboratory in Oklahoma City, most at a sample rate of 0.1 Hz. This series, transcribed to 9-track magnetic tape, includes windspeed and direction; temperature; vertical velocity at seven elevations; air pressure; wet-bulb temperature; pyranometer, and rain gauge readings from selected elevations. We used the windspeed data recorded at 26 m for the model because this elevation most closely matches the equatorial elevation of the VAWTs in which we are interested. The PDF of the series comes close to the Rayleigh distribution with a mean windspeed of 4.65 m/s (10.4 mi/hr) (Figure 10).

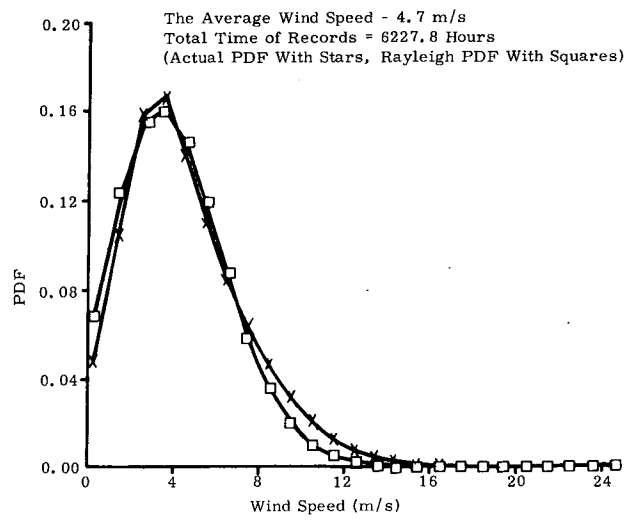


Figure 10. Comparison of WKY Tower PDF With Rayleight PDF

Besides the EPC of the Sandia/DOE VAWT, we have used two other curves:

- An EPC generated by the computer code PAREP[2] for a 17-m VAWT turning at 2.6, 3.14, 3.66, 4.19, and 4.71 rad/s (25, 30, 35, 40, and 45 rpm)
- An EPC from a one-parameter family of piecewise linear curves defined by the function

$$P(V) = \begin{cases} -6\text{kW for } 0 \leq V \leq V_0 - 2.2 \\ 2.7^* (V - V_0) \text{ for } V_0 - 2.2 \leq V \leq 3^* V_0 - 6.6 \\ 5.4^* V_0 - 18 \text{ for } 3^* V_0 - 6.6 \leq V \end{cases}$$

where V_O is the cut in windspeed, satisfying $P(V_o) = 0.0$; this EPC gives wide variation in turbine characteristics that depend on one parameter.

Subsequently, we conducted tests with the automatic control simulator, using only the moving-power algorithm because it had clearly outperformed the other three, purely electronic, algorithms and performed almost as well as the coasting algorithm.

Dependency of the maximum algorithm efficiency on the EDF may take many forms. After we found the maximum efficiencies for several cases by running many tests of the automatic control simulator corresponding to different data sets, we plotted the maximum algorithm efficiency against various properties of the EDFs. Two clear relationships emerged, either of which may be used to determine the approximate maximum algorithm efficiency corresponding to a given EDF. The first (Figure 11) is between the maximum algorithm efficiency and the slope of the EDF at the cut-in windspeed, E_o. The second (Figure 12) is between the maximum algorithm efficiency and the ratio

$$R = \frac{V_m - V_o}{V_o},$$

where V_m is the windspeed at the maximum EDF and V_o is the cut-in windspeed.

In Figures 11 and 12, we see that the maximum algorithm efficiency may be given as a function of either E_o or R. This functional relationship may be used to select an economical VAWT for a given site or, more basically, to determine if a VAWT is badly suited, so far as controlling it is concerned, for a turbine site. For example, the Sandia 17-m VAWT would be ill-suited for Oklahoma City, where it would produce a maximum algorithm efficiency of 72%.

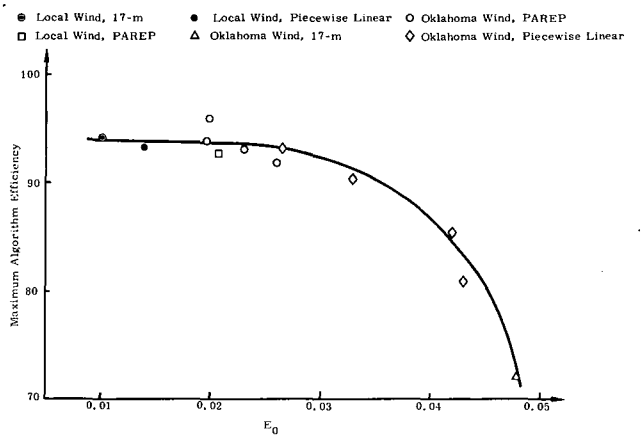


Figure 11. Maximum Algorithm Efficiency vs E_O

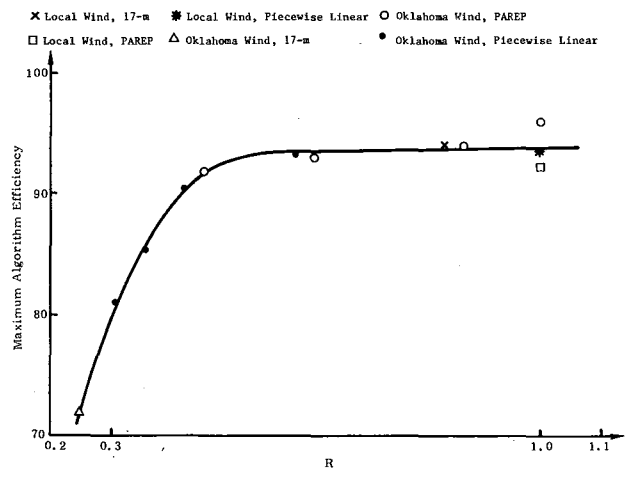


Figure 12. Maximum Algorithm Efficiency vs R

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[2]T. Leonard, *A User's Manual for the Computer Code PAREP*, SAND79-0431 (Albuquerque: Sandia National Laboratories, April 1979).

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