Methods for Performance Evaluation of Synchronous Power Systems Utilizing the Darrieus Vertical-Axis Wind Turbine

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Abstract

Methods for calculating wind energy extraction by Darrieus vertical-axis turbines driving synchronous generators are developed. Included are the effects of turbine power coefficient, blade tip speed, generator and transmission efficiencies, and wind conditions. Example problems, using two different wind speed distributions, are presented to demonstrate the methods. A simplified economic analysis indicates that system design parameters which yield minimum cost systems are quite sensitive to wind conditions and relative component costs. Use of the methods to effect improved economic analyses is discussed.
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Methods for Performance Evaluation of Synchronous Power Systems Utilizing the Darrieus Vertical-Axis Wind Turbine

Introduction

Use of the Darrieus vertical-axis wind turbine to drive a synchronous generator in parallel with a synchronous electrical power network has been described in a previous report.\(^1\) Aerodynamic characteristics of the Darrieus vertical-axis turbine can be such that, with proper generator sizing, no torque regulation mechanisms need be provided on the turbine. Synchronization to maintain constant turbine rotational speed is provided by the network.

This report is intended to add to the qualitative ideas of Reference 1 by examining some quantitative aspects of synchronous power generation. Specifically, methods are developed which consider the effect on system output of turbine power coefficient, transmission efficiency, generator efficiency and rated power, wind conditions, and turbine size and rotational speed. Performance models which account for such variables have been devised to analyze propeller-type systems,\(^2,3\) but involve an arbitrary choice of rated power. As will be shown, a feature of the performance model for Darrieus vertical-axis wind turbine systems is that maximum turbine power is uniquely determined by turbine aerodynamic characteristics, swept area, and tip speed.

The remainder of this report is in five sections. Models which characterize the turbine, transmission, generator and wind conditions are described. The component models are combined to develop analytical expressions for system performance; the model is exercised using two example wind distributions and using ideal and practical component efficiencies for comparative purposes. As a first approximation to an economic analysis designed to minimize cost and maximize energy
production, three types of system design optimization are considered, based on the following: (a) maximization of energy per unit swept area, (b) maximization of energy per unit generator rated power and (c) designs which fall between the limits provided by (a) and (b). Results from the simplified economic analysis indicate that component costs influence to a great extent the selection of optimum designs. Application of the performance model presented here to a more refined economic analysis is discussed. Finally, the report concludes with directions for further efforts.

System Component Characterization

1. Wind Turbine Characterization

In the case of power generation by synchronous wind turbines, the relationship of interest is that of turbine power to wind speed for a fixed rotational speed.\(^1\) This relationship is derived from the more typically used measure of turbine performance, the power coefficient. Turbine power is given on a per unit swept area basis with tip speed as a parameter, as this eliminates the need to specify the absolute size of the turbine.

The power coefficient is defined\(^4\) by

\[
C_p = \frac{P/A}{\frac{1}{2} \rho V^3}
\]

where \(P/A\) is the aerodynamic power extraction per unit swept area in a flow with density \(\rho\) and speed \(V\). Physically, \(C_p\) represents the ratio of energy produced by a turbine to the energy contained in the wind passing through the turbine swept area.* In general, \(C_p\) is a function of the tip speed

*For propeller-type wind turbines, it is not theoretically possible\(^5\) to extract energy with \(C_p\) greater than 0.593.
to wind speed ratio, $R_w/V$, where $R$ and $\omega$ are the maximum radius and the rotational speed, respectively, of the turbine.

The power coefficient function used for the examples in this report is shown in Figure 1. This curve is derived from experimental measurements on a 15 foot diameter, three-bladed Darrieus vertical-axis wind turbine. A maximum power coefficient of 0.36 occurs at a tip speed ratio of 4.7. The power coefficient function passes through zero at tip speed ratios of 2 and 7.

![Figure 1. Darrieus Vertical-Axis Wind Turbine Power Coefficient (from experimental data in Reference 6)](image)

Turbine power per unit swept area as a function of wind speed is readily derived by rearranging Equation (1) to give

$$P/A = \frac{1}{2} \rho V^3 C_p \left[ \frac{R_w}{V} \right]$$

(2)*

Figure 2 graphically depicts this relationship with tip speed as a parameter. Once a value for tip speed is chosen, it is evident that for some wind speed there is a maximum power per unit swept area, designated $P_{\text{max}}/A$, which will not be exceeded for any other wind speed. If the generator rated power is specified to correspond to this maximum, the generator pull-

*In this report a functional relationship will be denoted by square brackets.
out torque rating will not be exceeded and, therefore, no
torque regulation mechanisms are required on the turbine.\textsuperscript{1}

![Graph showing turbine shaft power for synchronous operation]

The quantity $P_{\text{max}}/A$ is shown in Figure 3 as a function of tip speed. It can be shown from the condition

$$\frac{\partial (P/A)}{\partial V} = 0$$

that the locus of maxima for the curves of Figure 2 is cubic with respect to tip speed, that is,

$$P_{\text{max}}/A = \frac{1}{2} cK(R\omega)^3,$$  \hfill (3)

where $K$ is a dimensionless constant related to the $C_p$ curve. The constant $K$ is equal to the maximum value of

$$C_p\left[\frac{R\omega}{V}\right]/\left(\frac{R\omega}{V}\right)^3$$

with respect to tip speed ratio. For the $C_p$ curve of Figure 1, $K = 0.00434$. 

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2. Transmission and Generator Characterization

A complete characterization of the transmission and generator would naturally require detailed information on the specific equipment types to be used. At this time the mechanical equipment has not been specified. Therefore, a method of accounting for losses is proposed which is analytically simple, yet representative of rotating machinery. When available, a more accurate scheme of loss accounting can be substituted in the analysis at this point.

The transmission and generator are characterized by a single relationship between input and output power. A three-parameter curve is shown in Figure 4. To specify the curve, the rated input power, $P_{ir}$, corresponding to the rated output power, $P_{rated}$, slope $\eta$ ($0 < \eta \leq 1$), and cut-off input power $X_{Pir}$ ($0 \leq X < 1$) are required.

The efficiency, $P_{out}/P_{in}$, of this system has the property of increasing as load approaches the rated capacity, and dropping to zero at the cut-off input power. The parameters $X$ and $\eta$ will in general depend on such variables as gear ratio, rotational speed, and power rating. For the examples in this
report \( \eta = 1 \), \( X = 0 \) representing ideal machinery and \( \eta = 0.78 \), \( X = 0.05 \) representing values appropriate to practical machinery will be used.

![Graph](image)

**Figure 4. Transmission and Generator Efficiency Characterization**

The analytical expression for the transmission and generator characterization shown in Figure 4 is given by

\[
P_{\text{out}} = \eta P_{\text{in}} - \frac{X}{(1 - X)} P_{\text{rated}} .
\]  

(4)

3. Wind Characterization

Wind energy extracted by a turbine over some interval of time (typically taken to be a year) is the integral of turbine power with respect to time over the given time interval, that is,

\[
E_T = \int_{\text{year}} P_T \, dt = \int_{\text{year}} \frac{1}{2} \rho A V^3 C_p \left[ \frac{R_w}{V} \right] \, dt .
\]  

(5)

For synchronous operation the turbine rotational speed \( \omega \) does not vary with time. In this case evaluation of the integral in (5) only requires wind speed as a function of time over a year. An equivalent, but more straightforward, evaluation of (5) uses the annual wind speed frequency distribution, \( f[V] \), a function of wind speed \( V \). The quantity \( f[V] \Delta V \) is interpreted
as the amount of time during a year that the wind speed falls in the interval \( V - \Delta V \) to \( V \). Using the wind speed frequency distribution in (5), the energy extracted by the turbine in a year is given by

\[
E_T = \int_{V_1}^{V_2} \frac{1}{2} \rho AV^3 C_p \left[ \frac{R_w}{V} \right] f[V] dV .
\] (6)

Where \( V_1 \) to \( V_2 \) is the interval of wind speeds for which \( C_p \geq 0 \).* For the \( C_p \) curve of Figure 1, \( V_1' = \frac{R_w}{7} \) and \( V_2' = \frac{R_w}{2} \) which depend on the tip speed.

Figure 5 depicts two example annual wind speed frequency distributions for Mt. Washington, New Hampshire,² and NASA's Plum Brook Station.⁷ These greatly dissimilar distributions were chosen for use in the systems analysis to indicate the effect of site selection on system design. Area under the annual wind speed frequency distribution is 8760 hours, the number of hours in a year. At Mt. Washington, average wind speed is 34 mph and at Plum Brook Station it is less than 10 mph.

**System Performance**

1. **Generator Rated Power Per Unit Swept Area**

   Referring to the input-output relationship for the transmission and generator as expressed in Equation (4), in order

*Wind speeds for which \( C_p < 0 \), i.e., the system draws energy from the network, will not be included in the computation of annual energy for the examples in this report. If such a condition persisted in actual operation, the system would be taken off-line. If, however, such a condition only occurred infrequently, the system might be left on-line and the absorbed energy should be counted against energy produced.*
that the generator rated power never be exceeded, the generator output, $P_{out}$, should equal the rating, $P_{rated}$, when the generator input, $P_{in}$, equals the maximum turbine power, $P_{max}$. This consideration requires

$$\frac{P_{rated}}{A} = \eta (1 - X) \frac{1}{2} cK(Rw)^3.$$  \hspace{2cm} (7)

Figure 6 shows $P_{rated}/A$ as a function of tip speed for ideal and practical machinery. In either case $P_{rated}/A$ depends on the cube of tip speed. To achieve a given generator rated power the effect of efficiency away from ideal is to require a greater swept area and/or a greater tip speed.

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**Figure 5.** Annual Wind Speed Frequency Distributions

**Figure 6.** Generator Rated Power Requirement
2. Annual Energy Per Unit Swept Area

Combining Equation (6) which expresses annual energy output from the turbine and Equation (4) to account for efficiency, annual energy output from the generator is given by

\[
E = \int_{V_1}^{V_2} \left\{ \eta \frac{1}{2} \rho V^3 C_p \left[ \frac{R_w}{V} \right] - \frac{X}{(1 - X)} P_{\text{rated}} \right\} f[V]dV
\]  

(8)

where \( V_1 \) to \( V_2 \) specifies the interval of wind speeds for which only positive generator output is achieved.* It can be shown that this interval is specified for a given tip speed by all wind speeds which satisfy

\[
\frac{C_p \left[ \frac{R_w}{V} \right]}{\left( \frac{R_w}{V} \right)^3} \geq XK
\]  

(9)

If the cut-off parameter \( X \) equals 0, then (9) reduces to the previously mentioned turbine constraint that \( C_p \geq 0 \).

Manipulating (8) and (7) leads to an expression for annual energy per unit swept area,

\[
\frac{E}{A} = \eta \int_{V_1}^{V_2} \frac{1}{2} \rho V^3 C_p \left[ \frac{R_w}{V} \right] f[V]dV - \eta X \frac{1}{2} \rho K(R_w)^3 \int_{V_1}^{V_2} f[V]dV
\]

(10)

which does not depend on the absolute turbine size but does depend on tip speed.

*As discussed in the previous footnote, practical considerations might dictate that the system be allowed to absorb energy if wind speeds outside the range of \( V_1 \) and \( V_2 \) occur infrequently.
Figures 7 and 8 show $E/A$ as a function of $R_w$. Dependence of $E/A$ on tip speed is quite strong, indicating that a value of tip speed must be carefully selected to give a desired value of $E/A$. For some value of tip speed, annual energy per unit swept area is maximized. The effect of efficiency away from ideal is to lower the $E/A$ curve and shift it toward lower tip speeds. Comparison of Figures 7 and 8 indicates that $E/A$ is quite site dependent.

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**Figure 7. Annual Energy Per Unit Swept Area at Mt. Washington Site**

**Figure 8. Annual Energy Per Unit Swept Area at Plum Brook Station Site**
3. Annual Energy Per Unit Rated Power

The ratio of $E/A$ to $P_{\text{rated}}/A$ expresses annual energy per unit rated power,

$$E/P_{\text{rated}} = \frac{1}{(1-X)K(R_w)^3} \int_{V_1}^{V_2} V^3 C_p \left[ \frac{R_w}{V} \right] f[V] dV - \frac{X}{(1-X)} \int_{V_1}^{V_2} f[V] dV .$$ (11)

which does not depend on the absolute turbine size nor the parameter $n$ but does depend on the tip speed.

Figures 9 and 10 show $E/P_{\text{rated}}$ as a function of $R_w$. Annual energy per unit rated power is maximized for some value of tip speed which, all other parameters being the same, is lower than the tip speed which maximizes $E/A$. The effect of the cut-off parameter $X$ is to lower and narrow the $E/P_{\text{rated}}$ curve, but the maximum always occurs at the same tip speed. Comparison of Figures 9 and 10 indicates that $E/P_{\text{rated}}$ is somewhat site dependent.

![Figure 9. Annual Energy Per Unit Rated Power at Mt. Washington Site](image)

![Figure 10. Annual Energy Per Unit Rated Power at Plum Brook Station Site](image)
System Design Optimization - A First Approximation

A critical measure of system worth is in terms of installed cost per unit energy produced. Reliable estimates of cost are unavailable at the present time for a synchronous electrical power generation system utilizing Darrieus vertical-axis wind turbines. The performance model described in the preceding sections can, however, be used to give qualitative indications which to some extent bound attractive system designs.

As a first approximation, suppose system cost can be represented by $C_1A + C_2P_{\text{rated}}$ where $C_1$ and $C_2$, assumed constant, are per unit costs of the turbine swept area and generator rated power respectively. It is desired to minimize the cost per unit energy produced given by

$$\text{Cost Per Unit Energy} = \frac{C_1A + C_2P_{\text{rated}}}{E}$$

where $E$ is the annual energy produced by a given design at a given site.

The minimum cost system will, of course, depend on the per unit costs $C_1$ and $C_2$. At this time, these costs are not known. However, regardless of the absolute values of $C_1$ and $C_2$, the optimum solution must lie between two extreme solutions which depend on the relative magnitudes of $C_1$ and $C_2$. The first extreme corresponds to maximizing $E/A$ (for $C_1 \gg C_2$) and the second to maximizing $E/P_{\text{rated}}$ (for $C_2 \gg C_1$).

These extremes are found in the following manner. Given an efficiency characterization, turbine aerodynamic characteristics, and a wind distribution, $E/A$ and $E/P_{\text{rated}}$ have been shown to depend only on tip speed. In fact $E/A$ and $E/P_{\text{rated}}$ each attains a maximum with respect to tip speed. Figures 11 to 14 show annual energy as a function of
turbine diameter* for designs which maximize E/A, labeled Curve 1, and designs which maximize E/P_{rated}, labeled Curve 2. All points on 1 have the same tip speed, that value which maximizes E/A. All points on 2 have the same tip speed, that value which maximizes E/P_{rated}. In either case tip speed determines P_{rated}/A. Furthermore, tip speed and a value of turbine radius determine the required rotational speed.

The curves of Figures 11 to 14 can be interpreted in the following manner:

(a) Curve 1 indicates the smallest turbine which will produce a given annual energy. At the same time, the required generator rated power is determined.

(b) Curve 2 indicates the smallest generator rated power needed for the production of a given annual energy. At the same time, the required turbine diameter is determined.

Two features of Figures 11 to 14 should be noted. First, for a given wind speed distribution, system designs based on maximizing E/A and E/P_{rated} differ greatly. This points out the need for an accurate assessment of relative component costs. Second, there is a wide variation in system design optima from site to site.

**Application of the Performance Model to a Refined Economic Analysis**

Methods have been presented in this report which address the performance of a synchronous electrical system utilizing Darrieus vertical-axis wind turbines. The model includes the influence of turbine size and rotational speed, aerodynamic characteristics, generator rating and efficiency, and wind conditions. System design optimization

*For the experimental turbine in Ref. 6, swept area is related to turbine radius by \( \frac{8}{3} R^2 \).
Figure 11. System Designs (Mt. Washington Site; $\eta = 1$; $X = 0$)

Figure 12. System Designs (Mt. Washington Site; $\eta = 0.78$; $X = 0.05$)

Figure 13. System Designs (Plum Brook Station Site; $\eta = 1$; $X = 0$)

Figure 14. System Designs (Plum Brook Station Site; $\eta = 0.78$; $X = 0.05$)
based on minimizing cost per net energy recovery was discussed for a cost function which depends linearly on turbine swept area and generator rated power. Use of such a cost function was convenient as a first approximation since energy per unit swept area and energy per unit generator rated power achieve maxima with respect to the single parameter tip speed.

It is noteworthy that the preceding "economic" analysis does not identify a unique system design as being best. This is an artifact of assuming that $C_1$ and $C_2$, the per unit costs of turbine and generator respectively, are constants. In reality, $C_1$ and $C_2$ are not constants but depend on the system parameters. A refined economic analysis is expected to not only isolate unique system designs but also indicate sensitivities of designs away from optimal.

Although a refined system cost function will be more complex than that used in this report, it should be noted that the performance model would still apply. Turbine radius and rotational speed would be varied independently to determine requirements on gear ratio and generator capacity and thereby efficiencies and costs. Given values for these parameters, the performance model would find the system energy output. Iteration would then identify the best system.

**Summary and Concluding Remarks**

The methods presented can be used in a straightforward manner to calculate output from Darrieus vertical-axis wind turbine systems. It has been shown that power output depends rather strongly on the selection of tip speed and, not surprisingly, wind conditions at the site.

The selection of appropriate operating conditions should be ultimately governed by the need to minimize costs. A very simple economic analysis, assuming the unit costs of the turbine and generator to be constants, indicates that the relative costs of these items have a
direct and significant influence on the selection of minimum cost operating conditions. It is concluded, therefore, that economics cannot be completely separated from the engineering of a Darrieus synchronous wind power system. A more complete, less simplistic, study of the economics is planned for the future.

This report has emphasized the development of calculational methods, with a few simple problems presented for illustrative purposes. However, many problem areas not addressed here can be examined with little extension of these techniques. Typical examples of such problems are a cost/benefit analysis of quasi-synchronous* operation, an understanding of turbine configuration as it effects output from changes in the $C_p$ curve and cost, and a performance comparison of vertical-axis systems to conventional propeller-type systems.

*The use of a variable speed gearbox to better tailor a wind turbine to seasonal or diurnal variations in wind speed.
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