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Development of an 8KW Wind Turbine Generator for Residential Type Applications

Phase I-Design & Analysis Volume I-Executive Summary

June 25. 1979

M. C. Cheney, et al

Prepared by
UNITED TECHNOLOGIES
RESEARCH CENTER
East Hartford, Ct. 06108

For
Rockwell International Corporation
Energy Systems Group
Rocky Flats Plant
Wind Systems Program
P. O. Box 464
Golden, Colorado 80401

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EXECUTIVE SUMMARY

INTRODUCTION

The Composite Bearingless Wind Turbine was developed at the United Technologies Research Center following many years of bearingless rotor research and development for helicopter applications. Wind turbine applications of this rotor concept were initiated in 1975 under an ERDA contract and subsequently a DOE design contract in 1976. The current 8 kW contract was begun in October 1977 with delivery of the prototype scheduled for November 1979. The contract consists of two phases. Phase I encompasses the complete design of the system and supporting analytical and experimental studies. The Phase I final report has been completed, and this executive summary highlights the principal findings described in that report. Phase II consists of fabrication and test, and eventually the delivery of the prototype to Rocky Flats for field evaluation. The completion of this last activity under the contract is expected in mid 1980 at which time a Phase II final report will be issued.

CONCEPT DESCRIPTION

The composite bearingless wind turbine was made possible by employing the specialized features of the Composite Bearingless Rotor (CBR), developed initially for helicopter application. The composite bearingless rotor evolved as a result of the unique application of fiber reinforced composite materials. The nonisotropic nature of unidirectional composites, generally considered an undesirable feature, yields a structure which is decidedly softer in torsion than in a direction which loads the fibers axially. By employing a finite length of this material at the blade root, torsional deflections can be achieved to satisfy the pitch angle change requirements of a helicopter rotor or wind turbine while providing sufficient stiffness in the in-plane and out-of-plane directions to satisfy hingeless rotor frequency requirements.

A general overview of the UTRC wind turbine is shown in Fig. 1, and a schematic of the basic components of the system are shown in Fig. 2. The blade is comprised of two distinct parts. The outer, or aerodynamic, portion of the blade is fabricated from fiberglass using a pultrusion process. The inner portion of the blade, called the flexbeam, is made up of unidirectional graphite epoxy. The dimensions of the flexbeam are dictated by the edgewise and flatwise frequency requirements, and the required torsional properties are determined

Fig. 1 UTRC Wind Turbine

Fig. 2 Wind Turbine Components

from the pendulum control system. The free length of the flexbeam runs from the hub to approximately 20 percent of the radius where it is joined to the fiberglass blade. As shown in Fig. 2 the outer portion of the flexbeam is connected to the pendulum through a steel strap, called the flexstrap. The flexbeam is layed up and cured in a preconed and pretwisted configuration, and extends through the hub and is connected to the opposite blade in a similar fashion. The flexbeam is pretwisted -16 degrees (leading edge into the wind) to place the blade in a position for self-starting. In this static condition the pendula are coned into the tower approximately 45 degrees by virtue of their connection to the flexbeam through the flexstraps. For optimum performance it has been shown that the blade pitch angle should operate in the vicinity of ± 2 degrees. This is achieved by virtue of the pendula acting under the influence of centrifugal force as rpm increases. The pendula begin to move towards the plane of rotation and, through the flexstrap connections to the flexbeam, provide a moment to the blades which twist the flexbeam thereby increasing the blade pitch. The pendula, acting against the torsional spring of the flexbeam, are always in moment equilibrium with the flexbeam.

The self-aligning feature of the CBR wind turbine results from the inherent dynamic response characteristics of low stiffness hingeless rotors. This arises from the phase lag of a simple spring mass damper system, wherein the mass experiences a finite lag between the time of excitation and the time of response. The duration of the lag is a function of the frequency and damping of the system. In the case of the wind turbine, which is yawed at an angle to the wind direction, the excitation results from the higher dynamic pressure of the blade rotating into the wind as compared to the blade moving away from the wind. These blades would be in their vertical positions when experiencing the greatest difference in lift. Their maximum flatwise deflection would occur at some position during the next quarter of a revolution. This in turn would produce a moment at the blade root which feeds directly into the hub. The turbine would respond to this moment and yaw in a direction to eliminate the differential lifts on the advancing and retreating blades. The motion would end when the blades are at equal lift which occurs generally when the turbine axis is aligned with the wind. In a free yawing system, such as that used for the CBR wind turbine, any wind direction change would create advancing and retreating blades and therefore the turbine would continuously self-align.

Under high wind speed conditions the wind turbine rotational speed would increase in proportion to wind speed if the pitch angle were left at its optimum value of ± 2 degrees. This would result in excessive tip speeds and thrust levels which, could potentially lead to a blade failure. Also, as RPM increases it will approach the blade edgewise frequency which would result in a coalescence with the one-per-rev gravity excitation creating a potential instability. The problem of overspeeding has been solved by producing stall on the rotor blades at a specific combination of wind speed and rpm. At a tip speed of approximately

122 m/s (400 f/s) which is approximately double the design rpm, the pendula will be essentially in the plane of rotation and produce a pitch angle on the blades of approximately five degrees. This angle, in combination to the aerodynamic angle produced by the wind speed, is sufficient to stall the blades. At this point the rotor tip speed is reduced and adjusts itself to a lower equilibrium which is approximately 90 m/s (300 f/s). The centrifugal force remains sufficiently high at this rpm to assist the blade in counteracting the root moment caused by blade thrust. The rotor will remain stalled until the wind speed drops below the stall point which is estimated to occur at approximately 22 m/s (50 mph).

Performance

A rotor diameter of 9.4 m (31 ft) was selected, producing more than the required 8 kW at 9 m/s wind speed, and also providing adequate residential power (approximately 2 kW) at low wind speeds (5.4 m/s), more typical of most residential areas. Performance was calculated for two rotor speeds, representing two different gearbox step-up ratios. The user would select the ratio depending upon whether he had high or low winds. The power output of the rotor for the two speeds is shown in Fig. 3, and the annual energy output is shown in Fig. 4. These results are for operation in conjunction with a utility where the induction generator operates at constant speed. The induction generator could be substituted with an alternator or a dc generator for stand-alone operation, however in this case the rotor speed would vary with wind speed and would produce dc or variable ac electricity. To obtain 60 cycle ac in this case an inverter would be necessary. A summary of the principal design parameters and performance characteristics are presented in the following table.

Rotor diameter	9.4 m (31 ft)
Number of blades	2
Chord	0.38m (15 in.)
Twist & taper	0
Pre-cone	8 deg
Airfoil	NACA 23112
Rated Wind Speed	9 m/s (20 mph)
Tip speed (low wind speed gearbox)	53.3 m/s (175 f/s)
Generator	15 kW induction type
Power at 9 m/s	9.5 kW
Annual power output at 5.4 m/s	23,000 kWh
Cut-in wind speed	4 m/s (9 mph)
Cut-out wind speed	35 m/s (78 mph)

Fig. 3 Rotor Power Output

Fig. 4 Annual Energy Output

SYSTEM DESIGN

Various trade-off studies were conducted to optimize the final prototype configuration. These studies examined parameters such as number of blades, diameter, solidity, blade construction, bending frequencies, generator type, gearbox ratio, and tower design. The primary objective of the design study was to achieve a design which had the potential for low production cost but also would minimize the technical risks of the prototype machine. When compromises were necessary, conservative decisions were generally made to enhance the success of the prototype.

Rotor and Pendulum

The rotor blade consists of an inboard flexbeam, spanning about 17 percent of the radius and carrying through the hub to the opposite blade, and an out-board airfoil region which produces the aerodynamic driving torque. The blade pitch control is derived from the pendulum motion through the flexstrap connection as described in the Concept Description section. The arrangement is shown in Fig. 5. The flexbeam is made up from unidirectional graphite/epoxy and is attached to the blade by means of an aluminum cuff. The blade itself is 100 percent fiberglass and is fabricated using a pultrusion process. The pultrusion technique was selected due to its potential for very low production costs.

Power Components

The main frame consists of a steel weldment with the various components mechanically attached. A schematic of the design is shown in Fig. 6. The main rotor shaft is supported at either end with roller bearings and drives the 2-stage step-up transmission through a flexible coupling. The transmission is base mounted to the main frame and the generator is C-face mounted to the transmission. A speed switch is provided, as shown, to connect and disconnect the grid at preselected shaft speeds. The system is free in yaw and supported through two roller bearings held within the tower cavity. Power and temporary instrumentation signals are transmitted through sliprings attached below the yaw bearings. A fiberglass fairing, consisting of three molded panels, provides weather protection for the power components.

Fig. 5 Hub & Pendulum Assembly

Fig. 6 Nacelle Components

Tower and Erection System

The tower consists of two 26 ft sections of 11 in. O.D. 1/4 in. wall steel pipe with a heavy baseplate welded at one end and slip-on flanges welded at the other free ends. The center flanges are bolted together and provide the attachment for the lower guy wires, and the upper flange is mated with the flange holding the yaw bearings and also provides the attachment for the upper guy wires. Tower erection is achieved through the use of a gin pole and an 8000 lb capacity winch. The tower and erection procedure is shown schematically in Fig. 7.

ESTIMATED PRODUCTION COSTS

A detailed estimate of the total system cost is presented in the Phase I report. Assumptions in the estimate include: 1977 dollars, production rate of 1000 units per year, burdened labor rate of 12 \$/hr, and a mark-up of 40 percent on all materials and purchased parts. The following table summarizes the major component costs.

Cost Summary

<u>Component</u>	<u>Labor</u>	<u>Material</u>	<u>Total</u>
Blades	\$ 364	\$ 369	\$ 733
Flexbeam, Hub & Controls	372	763	1135
Power Components & Support Structure	912	4493	5405
Tower	121	2493	2614
Packaging & Misc	<u>180</u>	<u>340</u>	<u>520</u>
Total	\$1949	\$8458	\$10407

Additional costs which one must incur before the system becomes operational are shipping and installation. These are expected to add 15-20 percent.

Fig. 7 Erection Procedure

CONCLUDING REMARKS

The design studies and supporting analytical efforts have shown the 8 kW prototype to satisfy the program objectives relative to performance and operational characteristics. Stability and loads calculations, using established helicopter aeroelastic codes, have demonstrated the system to be well damped under all loading conditions and to operate well below allowable stress levels. System costs are running about 20 percent higher than the contract goals; however reductions in the main frame and tower costs appear feasible and would be explored in a second generation 8 kW design.