Performance and Evaluation of a Variable-Speed Darrieus Wind Turbine

Kasey W. Abbott
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PERFORMANCE AND EVALUATION

OF A

VARIABLE-SPEED DARIEUS WIND TURBINE

BY

KASEY W. ABBOTT

A Thesis submitted
in partial fulfillment of the requirements
for the degree Master of Science, Major in
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1982
PERFORMANCE AND EVALUATION
OF A
VARIABLE-SPEED DARRIEUS WIND TURBINE

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Leslie L. Christianson Date
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INTRODUCTION

Developing wind energy suitable for agriculture applications is a critical step towards providing a reliable, affordable energy supply for United States agriculture. United States agriculture, due to its energy intensive nature, is dependent on petroleum fuels. Because agriculture is extremely sensitive to supply interruptions, steps must be taken to reduce this dependence on oil, including developing wind energy systems. It appears that the potential is there since winds over the United States contain more than 30 times the total energy consumed in this nation (Soderholm, 1979).

Agricultural applications (e.g. irrigation pumping, product processing and building heating) are uniquely suited to the variable power produced by the winds because many agricultural tasks can effectively use variable rates of energy supply. Many agricultural tasks can tolerate short energy interruptions and are easily adapted to inexpensive storage (Hunt, 1981).

The economical viability of wind energy for agricultural applications is highly dependent on initial costs and total energy produced. Darrieus wind turbines are one of the most promising models because of relatively low capital costs inherent in the simple design (Sullivan, 1979). The Darrieus is a vertical-axis machine that resembles an egg beater. It needs no yaw control mechanism, since it accepts wind from any direction, and power conversion equipment can be located on the ground, due to its vertical shaft. Two methods of supporting the Darrieus are the cable tie-down system and cantilevered system. The cable tie-down
support method uses several guy cables which are connected from the ground to the top of the turbine rotor. The cantilevered system, which supports the rotor only at the base, is simpler since there is no need for guy cables, cable anchors and tensioning mechanisms. Vibration problems with the guy cables are also eliminated (Karnitis, 1980). Most Darrieus turbines operate at a constant rotational speed to better adapt the systems for electric power generation, however, variable-speed Darrieus turbines have higher efficiencies and a higher potential power output (Karnitis, 1980). Many agricultural applications can use the direct mechanical energy generated by the wind turbine. Losses caused by the intermediate generation of electricity as well as the capital costs of the additional equipment are thus avoided (Black, 1981). However, operating the Darrieus in a variable-speed mode poses problems in limiting vibrations and rotational speeds. Load matching to maintain optimal performance may also be difficult.

Therefore, research was initiated to design, construct and test a variable-speed cantilevered Darrieus for agricultural applications. The principal objectives were:

1. Design a Darrieus system suitable for variable-speed operation.
2. Construct a Darrieus according to the proposed design.
3. Develop a suitable testing procedure for a variable-speed Darrieus system.
4. Test and evaluate the performance of the variable-speed Darrieus system.
(5) Compare the efficiency measured during variable-speed operation with the theoretical efficiencies of constant-speed operation.
LITERATURE REVIEW

Wind Energy Availability

Wind power per unit area is a function of wind speed and air density. This power results from the kinetic energy of the moving air and from the air mass flow rate:

\[ P = 0.5 \rho A v^3 \]

where

- \( P \) = potential wind power, W
- \( A \) = cross sectional area, \( m^2 \)
- \( v \) = velocity of the wind, m/s
- \( \rho \) = air density, kg/m\(^3\)

Wind speed is the primary influence on wind energy because of the cubic relationship. For example, a 15 m/s wind contains 3.375 times more energy than a 10 m/s wind. This relationship makes site selection extremely important. Air density is a function of temperature, pressure and relative humidity. However, according to Johnson (1978), relative humidity affects the density by less than one percent and is consequently dropped from the equation. The equation then becomes:

\[ \rho = 1.2929 \left( \frac{Pr}{760} \right) \left( \frac{273}{T} \right) \]

where

- \( \rho \) = air density, kg/m\(^3\)
- \( Pr \) = pressure, mm of Hg
- \( T \) = temperature, \(^0\)K

Wind energy available in the surface winds over the United States equals more than 30 times the total amount of energy that the United States consumes in a year (Soderholm, 1979). Blackwell and Feltz (1975) state that wind turbines spaced 10 turbine-diameters
apart throughout the Great Plains could provide up to 40 percent of the 1973 United States electrical energy consumption. However, it would take a million, 1 MW-rated turbines to convert all the wind energy available in the Great Plains.

Significant wind energy exists in the north central region of the United States. According to the DOE (1981), 70 percent of the land in the area consisting of South Dakota, North Dakota, Iowa and Minnesota has a wind power density greater than or equal to 150 W/m$^2$ at an elevation of 10 m. South Dakota is second in wind energy potential to North Dakota in the North Central Region. Over 53 percent of South Dakota has a wind energy density greater than 200 W/m$^2$ at 10 m (DOE, 1981). Average wind power for Brookings, South Dakota at 10 m is 100 W/m$^2$ (Lytle, 1982).

Wind energy potential varies significantly due to elevation, location and time. At increased heights surface effects become less of a factor and wind velocities increase. According to Clark (1980), the most common equation to represent the relationship between increased wind speed and height is:

$$V_2 = V_1 \left(\frac{h_2}{h_1}\right)^{1/7}$$

where $V_2$ = wind speed at new height ($h_2$)  
$V_1$ = wind speed at old height ($h_1$)

Since wind energy is proportional to the cube of the wind velocity the wind power would therefore increase to the three-seventh power of the height above the ground.

Wind power variations due to location are shown in Figure 1. These variations are primarily due to large scale patterns of pressure
systems, local topography, and local heating or cooling (DOE, 1981). Local terrain effects (e.g. valleys, hills or dense vegetation) can change actual wind power at a site by 50 to 100 percent from predicted values. In South Dakota wind energy is generally less in the southwestern and southeastern areas of the state (DOE, 1981).

Wind power availability changes yearly, seasonally and daily. In 1976 the average wind speed was 30 percent larger than in 1974 for Brookings, South Dakota (Lytle, 1982). In the north central region wind power is highest during the spring and least during the summer. Average wind speeds in April are 30 percent higher than average wind speeds in July for Huron, South Dakota. Daily wind power levels also vary (Figure 2).

Agricultural Wind Energy Applications

Wind power can be applied to agriculture for many purposes. The feasibility of using wind energy for an agricultural application is dependent on the following factors: (1) high annual utilization, (2) used in regions or seasons of high wind, (3) interruptible power supply is satisfactory (or inexpensive storage is available), (4) uses a large amount of energy (Liljedahl, 1981). Agricultural applications that can directly use the variable, mechanical output from a wind turbine will be more economical than applications using wind-generated electricity, since losses caused by the intermediate generation of electricity are avoided and capital costs of the additional equipment are reduced (Black, 1981). According to Liljedahl (1979), applications that have potential to use wind energy and can operate directly by a
Figure 1. Annual average wind power at 50 m above higher elevations, in W/m². (Runt, 1981)

Figure 2. Diurnal variation in wind power for different months at Huron, South Dakota. (Verma, 1979)
wind turbine are product processing and storage, irrigation pumping and building heating.

Irrigation pumping is the largest energy user of this group. Irrigation uses 90 billion kWh of energy annually and accounts for 40 to 70 percent of the energy used on irrigated farms (Clark, 1981). In 1974 South Dakota irrigation required 44 million kWh of electricity, 2.65 million liters of gasoline, 15.4 million liters of liquid propane and 9.54 million liters of diesel fuel (Verma, et al., 1979). However, irrigation pumping generally occurs less than three months of the year, limiting the hours the wind turbine can be used and thus causing the wind energy system to be less cost effective (Liljedahl, 1979).

Heating requirements are the second largest on-farm energy user of which heating for farm dwellings is the primary component (Liljedahl, 1979). Heating requirements for buildings are directly correlated to wind velocity, which is helpful for matching energy supply to energy demand (Juddy, 1981). A 6.1-m wind turbine with a 10-kW generator used in conjunction with thermal storage can replace nearly two-thirds of the heating requirements in a warm climate and approximately one-third of the heating requirements in a cold climate (Stafford, et al., 1981). Heating of water requires one-third of the electricity used in rural areas (Liljedahl, 1979). Hot water requirements for dairy operations consumed nearly 2000 GW*h annually (Gunkel, et al., 1979).

Product processing and storage account for a large percentage of the energy required on certain farms (e.g. crop drying, milk cooking and grain drying). Crop drying uses 4.5 percent of all energy used
for agriculture (Hunt, 1981). In 1974 South Dakota used 19,000 liters of fuel oil, 4250000 m$^3$ of natural gas, 19 million kW-h of electricity and 81.6 million liters of liquid propane gas for crop drying (Verma, et al., 1979). Milk-cooling equipment requires approximately $5.3 \times 10^{15}$ J of energy annually (Klueter and Liljedahl, 1982). Milk cooling required 18 million kW-h of electricity for South Dakota in 1974 (Verma, et al., 1979). A heat pump driven by a wind turbine could heat water for sanitation and refrigerate milk for a dairy operation (Klueter and Liljedahl, 1982). Feed processing equipment such as grain grinders could be driven by a windmill, when wind is available, with the wind energy being stored as ground grain.

Rural areas, as opposed to more populated areas, are more suitable for the installation of wind turbines, since there is adequate land available and there is less problem with visual pollution, television interferences and acoustical noise (Soderholm, 1979). Visual pollution and acoustical noise need not be major problems for rural areas, since wind turbines can blend into the landscape and with small wind systems noise is minimal (Hunt, 1981). Television interferences can occur, however, within distances of two miles, and depend on parameters such as location, distance from transmitter and television channel (Hansen, 1980).

**Wind Energy Conversion Systems**

Wind turbines convert kinetic energy from air movement to mechanical energy in the form of rotary motion. This conversion takes place because of two aerodynamic forces: drag and lift. Wind machines
are classified according to whether drag forces, lift forces or a combination are the primary driving forces. Drag and lift forces can be felt by placing one's hand into a strong wind. When the hand is parallel to the wind no lift is produced but a slight amount of drag is present. Rotating the hand, one can feel lift and drag forces increase until at a particular angle the lift will decrease. Lift-driven windmills give the highest efficiencies although this efficiency depends on blade angle to the wind. This angle, called angle of attack, is very important in the operation of a lift-driven wind turbine (Hunt, 1981).

Wind systems are further categorized according to the axis of rotation relative to the wind direction. Horizontal-axis machines have an axis parallel to the direction of the wind while vertical-axis turbines have an axis perpendicular to the wind direction (Figures 3 and 4).

Wind turbines have traditionally been horizontal-axis machines. Examples of these are the American multi-blade and high-speed two bladed windmills (Figure 3). The American multi-blade has a high starting torque making it suitable for water pumping, but its low tip speed ratio makes it less efficient than other high-speed turbines. The two-bladed propeller turbine has received considerable attention because of its suitability for generating electricity and high efficiency. However, structural requirements and complexity for the two-bladed propeller turbine are higher than for other types of similar sized wind turbines (Blackwell and Feltz, 1975). Horizontal-axis rotors may also be fatigued by wind gusts since the yawing device cannot respond
Figure 3. Horizontal-axis wind machines. (Hunt, 1981)
Figure 4. Vertical-axis wind machines. (Hunt, 1981)
quickly to changing wind conditions (Houston, 1982).

Primary examples of vertical-axis turbines are the Darrieus and Savonius. The Darrieus has several important advantages over horizontal-axis wind machines, such as the high-speed propeller turbine. Darrieus turbines can accept wind from any direction thus eliminating the need for yaw control. Its vertical shaft allows power conversion equipment to be mounted near ground level which reduces tower structural requirements, lessens transmission requirements and assures easier maintenance (Karnitis, 1980). According to Sullivan (1979), other advantages include potential low-cost blade construction and aerodynamic stall characteristics at low tip speed ratios, eliminating the need for active rotational speed control. Disadvantages of the Darrieus are a lower aerodynamic efficiency than high-speed propeller turbines and the inability to self start. Fluctuation of torque output is also a problem but this effect can be minimized by using three blades.

The Savonius is a vertical-axis turbine that utilizes drag forces. It has a high starting torque and an efficiency of about 30 percent but requires 30 times more blade area than a conventional wind turbine for the same power output. Consequently, the Savonius is only practical for starting applications and light power requirements (Hunt, 1981).

Energy Conversion and Storage Systems

Mechanical energy from a wind turbine can either be used directly or converted to electrical energy. Directly using the mechanical energy results in high efficiencies but causes difficulties in limiting
rotational speeds and may limit the system's annual use. Converting the energy from mechanical to electrical gives lower efficiencies but increases the versatility of the system. Energy conversion systems can usually be made more effective by interfacing them with other sources of power or using storage mediums.

Wind turbines frequently are used to produce electricity because of the ease of load matching between turbines and generators (Nelson, 1982). To produce electricity at the same voltage and frequency as utility power, wind turbines usually power synchronous generators which operate at a constant rotational speed. Darrieus turbines used to power synchronous generators are self-braking because at high wind speeds they become less efficient, causing the turbine to stall. However, this mode of operation increases the capital costs and lowers the efficiency of a wind energy system (Hunt, 1981). Field modulated generators are being developed that can utilize variable power input and produce alternating current power output by electronic compensation. This would improve efficiencies but increase system complexity and cost (Hunt, 1981).

Directly using the mechanical energy from the turbine eliminates inefficiencies that occur in the generation of electricity and reduces capital costs since electrical generation equipment is not needed (Black, 1981). Disadvantages of the system include controlling turbine rotational speed and possible limited annual use. Turbine rotational speeds need to be controlled because of the large centrifugal forces that develop if the turbine is allowed to overspeed, resulting in possible failure of the wind turbine. Unlike electrical systems,
mechanical systems have difficulty in limiting rotational speed because there is no ready method of rotational speed control. Karnitis (1980) suggested matching the load so that it reaches maximum turbine torque at the rotational speed limit forcing the turbine to stall. Other approaches would involve spoiling the rotor performance by various means to limit speeds. Limited annual usage can be a problem because storing or transporting mechanical energy is difficult. For example, a Darrieus directly coupled to an irrigation pump provided 12 percent more power to the pump than did wind turbines that produced electricity. However, since the system could only be used on site when water was needed, annual per unit energy costs were 2.5 times as high with the mechanical system as with the electrical system (Clark, 1981).

Applications, using the direct mechanical output from windmills, include: irrigation pumping, product processing and storage, and building heating (Liljedahl, 1979). Converting the mechanical output to thermal energy appears to show the most promise, since the efficiency is higher than electrical generation and the thermal energy can be used year round for space heating, water heating and crop drying.

Thermal energy can be produced by a fluid agitator or heat pump directly coupled to a wind turbine. Mechanical dissipation systems, where the kinetic energy of the rotor is transformed into thermal energy by agitation of a fluid, are nearly 100 percent

\[1\] Making the turbine less efficient by altering the aerodynamic performance.
efficient. Efficiency being reduced only by heat loss from the system and any friction heat loss outside of the storage unit (Gunkel, et al., 1979). These systems are less expensive than other wind energy thermal systems because of their simple design (Figure 5). Because of its low cost and high efficiency, some researchers believe that water can be heated with these systems for as low as $.023/kWh (Bollmeier, et al., 1980). Mechanical heat churns are also inherently compatible with wind turbines, since both are basically propeller-in-fluid processes that operate with a cubic power/speed relationship. The agitator unit can be designed so that it will fully utilize the variable power of the wind energy system at all speeds. Due to this relationship a turbine-agitator system can operate in a variable-speed mode, maximizing power output as the wind speed changes and being speed controlled by the agitator device (Gunkel and Lacey, 1980).

A heat pump directly connected to a wind turbine will have a coefficient of performance (COP) of approximately two and can provide both heating and cooling (Figure 6). Heat pumps take heat from the ground, water, outside air, or some other heat source, and deliver it together with the heat equivalent of the compressor work (Karnitis, 1980). Heat pumps also provide cooling since they take heat from one source and deliver it to another. For example, mechanical refrigeration equipment can be expected to have a COP of 2.5; for 1 joule of mechanical work supplied by a wind turbine, 2.5 joules of cooling and 3.5 joules of heating would be transferred for a useful power output of 6 joules (Klueter and Liljedahl, 1982).
Figure 5. Closed tank and components. (Gunket, et al., 1979)
Figure 6. General-system schematic of a wind driven heat pump for milk cooling and water heating. (Klueter and Liljedahl, 1982)
Heat pumps operated in this manner pose several design problems. Load matching is difficult because heat pumps are designed to operate at a constant rotational speed and with a constant refrigerant flow, however, to obtain maximum efficiency from the wind turbine, the system must operate in a variable-speed mode (Gunkel, 1982). Heat pumps can be modified to allow the compressor powering the heat pump to vary in rotational speed. For example, automotive air conditioning systems operate in a variable-speed mode by bypassing excess refrigerant to maintain a constant flow of refrigerant (Karnitis, 1980). However, although compressor speed can be allowed to vary, the torque on the compressor is nearly constant. The power required by the heat pump is then directly proportional to the wind speed. This is not an ideal match for the turbine as the power available from the turbine is proportional to the wind speed cubed (Figure 7).

Two possible methods of improving the efficiency of a wind energy heat pump system are the step-wise loading systems and the variable-ratio transmission systems. The step-wise loading system uses multiple compressors that can be connected to the wind turbine by a clutching arrangement. As the wind speed increases more compressors could be driven by the turbine (Figure 8). This method has been used when the refrigeration load has varied but has not been used with wind energy systems. Compressor cycling may occur which may damage the compressors, if the turbine operates at rotational speeds near the switching points. Operational controls are needed to prevent the compressor from starting within several minutes of stopping (Klueter and Liljedahl, 1982).
Figure 7. Power generated by a single compressor driven through a fixed ratio and total power in wind. (Klueter and Liljedahl, 1982)
Figure 8. Stair-step matching with three compressors. (Klueter and Liljedahl, 1982)
Variable-ratio transmission systems are more complicated than the step-wise systems but have higher efficiencies. Since the torque on a simple compressor remains fairly constant over varying speeds, a variable-ratio transmission between the wind turbine and compressor can be used to make the torque on the wind turbine proportional to the wind speed. If the torque on the turbine shaft is proportional to the wind speed squared, ideal load matching is achieved. This can be accomplished by making the transmission ratio proportional to the wind speed squared (Figure 9), (Klueter and Liljedahl, 1982).

Difficulties occur with this design because the ideal operating speed range for a compressor is approximately 3 times the minimum operating speed, yet to match the wind turbine output the compressor would need a speed range approximately 27 times the minimum operating speed. Proper load matching with this system would therefore require three compressors with displacement sizes fitting a 1:3:9 ratio and operating over three different speed ranges (Figure 9). The high efficiency of this system is obtained at a considerable increase in system complexity and capital cost. Several compressors, clutches and variable ratio transmissions are needed, as well as separate anemometers in order to switch compressors (Klueter and Liljedahl, 1982).

Selection of the optimal heat pump for use with a variable speed wind turbine involves a complex interplay of performance and cost parameters. By increasing the range of the compressors and/or reducing the number of compressors the system cost decreases at the expense of lowered efficiency.
Figure 9. Load matching with variable ratio transmission and multiple compressors. (Klueter and Lilijedahl, 1982)
Utilization effectiveness of a wind energy system can be improved by interfacing with other power sources or by using them in conjunction with an energy storage system. Additionally, interfacing with other power sources or providing storage results in improving energy supply reliability for the particular end use.

Wind energy systems are interfaced with utility grids and diesel generators. By interfacing wind turbines with utility grids, rather than providing on-site battery storage, and associated inverting equipment the cost of generating electricity is decreased by about 50 percent (Liljedahl, 1979). With the utility interfaced system a wind turbine is connected in parallel with the electric grid network and electricity is supplied to the load when wind energy is not available. The primary advantage of this is that power is available on demand (Nelson, 1982). A Darrieus powering an irrigation pump in parallel with an utility system took full advantage of available wind energy and still maintained a uniform output which resulted in savings of 65 percent in energy costs (Clark, 1978). Wind assist systems can also sell excess electricity to the utility company at a wholesale price (Soderholm and Clark, 1981).

Wind-solar interfaced systems have been proposed because combining alternate energy systems increases the uniformity and dependability of power output. Karnitis (1980) states that wind and solar energies could be combined in a system to make the yearly energy density flux more uniform (Figure 10).

Using storage mediums in conjunction with wind energy systems can improve economic feasibility. The optimal method of using small
Figure 10. Yearly variation in wind and solar (horizontal) energies for Huron, South Dakota. (Verma, 1979)
Wind energy thermal systems is by utilizing heat storage with water, stones, or concrete (Juddy, 1981). Soderholm and Clark (1981) state that a 90 percent wind energy utilization efficiency can be achieved from a well insulated 2300 L storage tank of water with a 10-kW wind turbine. Flywheels can also store energy while providing a more uniform power output and reduced torsional vibrations (Klueter and Liljedahl, 1982).

Wind Energy Economics

Cost of power generated by a wind energy system over its lifetime must be less than the cost of power generated by other alternatives in order for the wind energy system to be economical. Cost of wind generated power is dependent on the mean wind speed, capital costs and energy utilization.

Locating the turbine near areas of high average wind speeds has the largest effect on the cost of wind generated energy. Decreasing a mean wind speed of 3.8 m/s by 20 percent produces a 88 percent increase in unit energy cost. However, a 20 percent increase in a mean wind speed of 3.8 m/s decreases unit energy costs by only 34 percent because of rotational speed limitations of the turbine (Gunkel, et al., 1979).

Wind energy capital costs include turbine and financing costs, maintenance, insurance, property tax, and tax credits with initial turbine costs and available tax credits being the most important factors. Turbine costs depend primarily on turbine size and structural requirements. Wind turbines have generally been considered to be less cost effective as size decreases, primarily because factors such as labor and electrical system costs are
relatively constant for various turbine sizes (Kadlec, 1978). However, small wind machines have reduced development costs and technical risk, as well as markets that only small wind turbines can serve because of demand limitations. These factors can improve the feasibility of small wind systems (Kadlec, 1978) and (Sullivan, 1979). Additionally, small wind systems are more suited for mass production, can be more easily transported, require less skilled labor and can be sited closer to the load than large scale wind turbines (Bauman, et al., 1981). According to a recent study, the most economical turbine to generate electricity for farm tasks is approximately 10-kW (Buzenberg, et al., 1979). Structural requirements of the turbine are dictated by peak loads which normally occur at cut-out speeds. Designing small wind machines to operate in wind speeds higher than 16 m/s or less than 4 m/s is generally not worthwhile because of the limited annual power available at these speeds (Figure 11). Tax credits can significantly reduce the cost of a wind energy system. Current federal solar tax credits give a 40 percent credit on the first $10,000 of a wind system for an individual and a 25 percent credit for businesses with no upper limit (Nelson, 1982). Certain states also offer tax credits on wind energy systems.

Wind energy systems that produce the most energy annually, other factors being equal, will be the most economical. According to Stafford, et al., (1981) using wind energy systems for applications other than just space heating significantly increases the cost effectiveness of the system. Wind turbines installed in areas of high winds
Figure 11. Average wind power distribution for Amarillo, Texas at a height of 12.1 m.
(300 W/m$^2$ at 20 m) are not economically feasible if used only for crop drying, but if also used to generate electricity for other farm tasks, the turbines appear economically feasible (Garling, et al., 1980).

Wind energy systems that use the power produced on site will normally be more economical than those that sell excess generated power. Soderholm and Clark (1981), state that wind electric conversion systems can be optimized by using the power on site to replace "high-cost power" instead of selling it to utility companies at a lower wholesale price. Additional advantages are as follows: problems with metering, liability, undesirable interaction with the electric grid system and safety can be eliminated (Bauman, et al., 1981).

Darrieus Wind Turbines
Aerodynamic Performance

The Darrieus is a lift-driven machine with blades of symmetrical airfoil cross section attached at both ends of its rotating axis and bowed outward (Figure 16). The Darrieus works in this configuration because the wind velocity that acts on the blade is a component of both the actual wind and the relative wind while turning. These components form a resultant velocity that acts at a particular angle relative to the airfoil chord line, called the angle of attack, $\alpha$ (Figure 12). This velocity produces lift and drag forces which, when resolved along the blade chord line, determine the net force acting in the direction of blade rotation. The angle of attack that produces positive torque is typically between 2 and 15 degrees for symmetrical blades (Blackwell, et al., 1977).
Darrieus turbines stall at both large and small angles of attack. For a given angular position of a blade, relative to the wind direction, the angle of attack varies inversely with the tip speed ratio. The tip speed ratio is the ratio of the blade velocity to the wind velocity. As the tip speed ratio increases the angle of attack decreases for a given angular position of a blade (Figure 13). For low tip speed ratios, the variation in the angle of attack is large which causes the angle of attack to exceed the stall angle.\(^1\) For high tip speed ratios the angle of attack will always be small. If the angle of attack is sufficiently large or small the average axial force summed over a complete revolution can be negative, and the Darrieus will stall (Blackwell, et al., 1977).

Tip speed ratio is one of the primary means of characterizing the aerodynamic performance of the Darrieus (Figure 14). Tip speed ratio is defined as:

\[ X = \frac{R \omega}{V} \]

where

- \( X \) = tip speed ratio, dimensionless
- \( R \) = maximum blade rotor radius, m
- \( \omega \) = rotor angular velocity, rad/s
- \( V \) = wind velocity, m/s

Darrieus efficiency reaches a maximum at a certain tip speed ratio for constant rotational speed applications (Figure 14) and the

\(^1\)The angle of the blade chord to the relative wind direction at which the torque applied to the rotor becomes negative.
Figure 12. Relative velocity and aerodynamic forces for typical blade element. (Blackwell, et al., 1977)

Figure 13. Angle of attack as a function of blade angular position (equatorial plane). (Blackwell, et al., 1977)
Figure 14. Power coefficient, $C_p$, performance data for 5-meter turbine with three extruded NACA-0015 blades at 125, 137.5, and 150 rpm (Sheldahl et al., 1980).
Darrieus will stall at high and low tip speed ratios (Blackwell, et al., 1977).

Since the Darrieus is a lift driven device, the blade Reynolds number affects performance slightly. Blade Reynolds number is defined as:

\[ \text{Re}_c = \frac{cR\omega}{u} \]

where \( \text{Re}_c \) = blade Reynolds number

\( c \) = chord length, m

\( R \) = rotor maximum radius, m

\( \omega \) = rotor angular velocity, rad/s

\( u \) = air viscosity, m\(^2\)/s

Increasing the Reynolds number increases the maximum power coefficient and the range in tip speed ratios of useful power output (Figure 14).

Turbine parameters that affect the aerodynamic performance of the Darrieus are rotor height to diameter ratio and rotor solidity. Rotor height to diameter ratio is defined as:

\[ \lambda = \frac{H}{D} \]

where \( \lambda \) = rotor height to diameter ratio, dimensionless

\( H \) = rotor height, m

\( D \) = rotor maximum diameter, m

There is no significant advantage in designing a Darrieus to have a height diameter ratio larger than one (Templin, 1974) or between two-thirds and one (Reuter and Sheldahl, 1976). Presently, most Darrieus turbines have a height diameter ratio near one or slightly larger.
Rotor solidity has a larger effect on turbine performance. 

Rotor solidity is defined as:

\[ \sigma = \frac{Nc}{R} \]

where \( \sigma \) = rotor solidity, dimensionless
\( N \) = number of turbine blades
\( c \) = airfoil chord length, m
\( R \) = rotor maximum radius, m

As solidity decreases the entire efficiency versus tip speed ratio curve is shifted to higher tip speed ratios. If a maximum power coefficient is desired, solidity of a turbine should be between 0.2 and 0.25 (Blackwell, et al., 1977).

Darrieus Operational Systems

Since performance of the Darrieus is dependent on the tip speed ratio and blade Reynolds number, the method of operating the Darrieus can drastically affect overall performance. For optimal performance, the Darrieus operational speed varies as the wind speed varies, to maintain a constant tip speed ratio corresponding to highest efficiencies. However, most Darrieus turbines are operated at a constant rotational speed in the synchronous generation of electricity. Since the rotational speed is constant, the tip speed ratio and hence the efficiency are a function of wind speed. Consequently at high wind speeds (the tip speed ratio is low), efficiency will be low. This low efficiency at high wind speeds results in a lower power output than would be possible under a variable-speed system (Thresher and Wilson, 1976). Variable-speed systems allow the
rotational speed to vary with the wind velocity to maintain a tip speed ratio which results in high efficiency (Karnitis, 1980).

Hypothetical improvement in efficiency by operating the Darrieus in a variable-speed mode ranges from 10 to 21 percent (Sullivan, 1976) and (Blackwell, et al., 1977). More research is needed to verify how much more efficient the variable-speed operational mode is than the constant-speed mode.

Disadvantages of operating the Darrieus in a variable-speed mode are in controlling vibrations and limiting rotational speeds. Optimal load matching is also difficult to achieve with variable-speed Darrieus systems. Little is presently known on the severity of these problems as most Darrieus turbines are operated at constant rotational speed to generate electricity. Since these disadvantages can limit the effectiveness of a variable-speed Darrieus system, research is needed to determine how severe these problems are and how they can be controlled.

Sandia Laboratories tested a Darrieus turbine in a variable-speed mode and did not experience resonance but discontinued operation because of the difficulty in taking data (Sheldahl, 1982). Also, a two-bladed, 4.3-m diameter Darrieus was tested by South and Rangi (1972) at variable-speeds up to approximately 160 r/min with no apparent difficulties. More research is needed to ascertain whether the Darrieus can safely operate in a variable-speed mode.

Vibrations occur in the operation of a Darrieus from either a mass imbalance or from resonance. If a significant mass imbalance
is present a counterweight can be used to dampen vibrations that occur (Rollins, 1982). Resonance occurs when the blade aerodynamic pulses occur at one-half or one-third the critical speed for a two-bladed or three-bladed Darrieus, respectively. Critical speed is the speed at which rotating shafts become dynamically unstable, and large vibrations develop. Critical speed can be increased by using turbine components that have adequate axial, bending and torsional stiffness components which keep the critical speed above the operating range of the Darrieus (Reuter, 1976).

Rotational speed control is a necessity for variable-speed systems. Large scale wind turbines have failed in England and the United States because the rotational speeds were not limited (Evans, 1978). Since the rotational speeds in a variable-speed system increase with an increase in the wind, brakes or blade spoilers must be used. Spring-loaded centrifugal spoilers mounted on the blades have been used to provide overspeed control for a variable-speed Darrieus (Hagen and Sharif, 1979). Spoilers must be carefully designed or they will lower efficiencies or even fail (Sheldahl, 1982). Centrifugally activated brakes can be used to brake the turbine when a certain rotational speed is exceeded (Houston, 1982).

Proper load matching for a wind energy system is necessary if adequate performance is to be achieved. Load matching for constant-speed Darrieus systems has undergone considerable research but very little is known on successful design of variable-speed systems (Banas and Sullivan, 1976). Constant-speed systems are designed to operate at a rotational speed that when matched with the best speed for power
gives an optimal tip speed ratio. This wind-speed is determined by deriving a wind power duration curve (Figure 11). Variable-speed systems pose special load matching problems because the rotational speed varies to maintain a tip speed ratio corresponding to a high efficiency. Also, at a given optimal tip-speed ratio, when the wind speed doubles the available wind power increases by a factor of eight, turbine rotational speed doubles and turbine torque will approximately quadruple. Since many loads have roughly a constant torque for any given rotational speed, runaway conditions would exist and efficiency would decrease (Figure 7). Darrieus turbines connected to variable-speed loads operate at a point where the turbine torque versus turbine rotational speed curve intersects the load torque versus load rotational speed curve (Figure 15). Although there are two points of intersection on the torque versus rotational speed curve only the right intersection is stable, since any small perturbation in rotational speed will result in differences in the load torque and turbine torque that will return the system to its equilibrium point (Banas and Sullivan, 1976).

Ideally, a turbine and load should be matched so that the resulting load curve will closely follow the maximum power curve of the Darrieus. In approaching this ideal for a variable-speed system, stalling may occur if winds are sufficiently gusty and the load is approaching the maximum torque output of the Darrieus. A sudden gust of wind can lead to a reduction in torque, thereby slowing the turbine down. If the wind remains at its higher speed the turbine eventually stops. Even if the wind returns to its original speed the turbine may still stop, if it slows enough during the transient
Figure 15. Performance characteristics of a Darrieus turbine and speed dependent loads (Blackwell et al., 1977).
wind. The stalling effect is difficult to predict because it depends on the specific shape of the load curve, the gustiness of the wind, and the inertia of the system. Stalling may be controlled by estimating the change in wind speed that would reduce the turbine torque below the load torque, then determining the likelihood of such a change in wind speed and designing accordingly (Banas and Sullivan, 1976). However, this method lowers system efficiency. A different method of controlling stall is to reduce the load when stall is sensed. This method has been used where either load B (alternator) or load C (DC motor/generator) could be selected (Figure 15). Load B was dropped if stall occurred and when operating conditions improved load B was selected again (Blackwell, et al., 1977). The Savonius has been suggested as a way to control stall. When stall occurred the load would be driven by the Savonius until operating conditions improved to where the Darrieus would once again take over. Although this eliminates any stalling problems the output of the system would be lower (Banas and Sullivan, 1976). The possibility exists that stalling may not be a problem for a variable-speed Darrieus. A variable-speed Darrieus mechanically coupled to a pump experienced no stalling even when the turbine was loaded so heavily that efficiencies were lowered (Hagen and Sharif, 1979).

Darrieus Design

Two basic designs suitable for supporting the Darrieus are the cantilevered and guyed. The majority of turbines are guyed, supported by cables attached to the top of the turbine. This simple design
results in a reduction of bending moment applied to the structure and increases the structural stiffness (Blackwell, et al., 1977). Guying the Darrieus decreases the structural requirements of the tower and according to Carne (1981) makes it generally more cost effective than other support methods. Major disadvantages of the guyed support are the potential for cable vibration, the increased land usage, the increased axial loads applied to the tower and bearings, and the difficulty in obtaining blade clearance for the cables (Blackwell, et al., 1977).

Cantilevered support is simpler since cables, cable anchors, and tensioning mechanisms to compensate for changes in temperature are not needed (Karnitis, 1980). Cantilevered support requires less land area per turbine and eliminates cable vibrations. Possible safety hazards due to the cables are also eliminated (Houston, 1982). Primary disadvantages of cantilevered support are its increased structural requirements. Alcoa reports that three out of five cantilevered Darrieus turbines have failed because the support bearings would wear out due to the higher fluctuating loads inherent in this design (Vosburgh, 1981). The Darrieus is also more susceptible to vibrations in this configuration due to mass imbalances (Rollins, 1982).

The Darrieus is normally started with an auxiliary device, usually a Savonius, or an electric motor. The Savonius has good starting torque and complements the Darrieus torque characteristics at low rotational speeds. However, the Savonius reduces the efficiency of the Darrieus and increases the structural requirements of the system (Blackwell, 1974). Electric motors can also start the Darrieus and
do not hinder the efficiency of the turbine but may be required about
20 times a day, just to start the Darrieus (Evans, 1978).

Blade to torque tube connections have undergone many design
changes. Originally blades were held by two clamp plates with the
airfoil shape cut into them. This was then attached to a terminal
plate supported at a fixed angle by a gusset (Figure 17). However,
many of the welds in this fixed angle arrangement developed cracks
which made the Darrieus unsafe. Since then manufacturers have been
utilizing various other devices to hold the blades (Vosburgh, 1981).

Proposed Darrieus Wind Energy Systems

A cantilevered Darrieus was designed and sized to be used
with the SDSU solar energy intensifier system for farm heating
applications (Darnitis, 1980). The Darrieus is designed to withstand
a 44 m/s wind speed in a parked position and a 19.8 m/s wind velocity
while operating. Height of the turbine is 8.3 m with a rotor diameter
of 4.6 m (Figure 16).

The NACA-0015 aluminum blades have a chord length of 152.4 mm
and a solidity of 0.067 per blade. The blade attachments consist of
two, 19.1 mm thick aluminum clamp plates into which the airfoil
shape is cut so that when the plates are brought together the blade
end is clamped securely (Figure 17). Clamp plate halves are tapered
over the outer 26.2 mm to reduce stress concentrations. The
split clamp is attached to a 6.4 mm thick aluminum terminal plate by
six, 9.5 mm diameter bolts.

The turbine torque tube is designed to resist wind induced
Figure 16. 5m Darrieus vertical axis wind turbine system (Karnitis, 1980).

Description
1. Airfoil
2. Torque Tube
3. Airfoil Attachment
4. Savonius Rotor
5. Tower
6. Concrete Pad
7. Upper Bearing Support
8. Lower Bearing Support
9. Caliper Disc Brake
10. Air Conditioning Compressor
11. Compressor Drive
Figure 17. Turbine blade attachment (Karnitis, 1980).

Description
1. Gusset
2. Clamp Plate
3. Clamp Plate
4. Turbine Blade
5. Terminal Plate
6. Torque tube
aerodynamic loads, thrust loads, cantilevered moments and the torque of the system. The aluminum torque tube has a 168 mm outside diameter and a 14.3 mm thick wall. The turbine is supported by two, tapered roller bearings designed to carry thrust and radial loads, and the misalignment of the turbine shaft, simultaneously. The upper bearing is designed for aerodynamic loads of the rotor and is a double-row, tapered roller bearing. The lower bearing is a single-row tapered roller bearing designed to resist radial and thrust loads of the turbine. Bearings are mounted on the turbine shaft and supported by four steel beams, 127 mm square with 9.5 mm thick walls, bolted to the tower legs. Each of the support arms is braced underneath by channel steel. The channel brace is welded to the support arm and bearing housing and is bolted to the tower leg.

Savonius rotors are attached to the torque tube to start the Darrieus and to minimize wind gust stalling. They are located at both ends of the rotor and are rotated 90 degrees from each other to ensure self-starting of the turbine.

The rotor and torque tube are supported by a 3.7 m four-sided steel tower which is 1.5 m square at the base and tapers to 0.8 m square at the top. The tower legs consist of 102 mm x 102 mm x 7.9 mm angle, diagonals are 76 mm x 76 mm x 6.4 mm angle, and side bracing is 89 mm x 89 mm x 7.9 mm angle. The corners and truss joints are reinforced by 4.8 mm steel plates.

Braking capabilities for the Darrieus is provided with a 50.8 cm diameter, mechanical caliper disc brake that is manually operated. The disc is mounted on the torque tube with the overall brake system mounted
on the top of the lower bearing assembly support arms (Figure 18).

The turbine is secured to the steel-reinforced, concrete foundation by four 19 mm thick steel anchor plates and 19 mm diameter anchor bolts. The foundation is designed to withstand wind forces and vibration of the system and is 2.3 m square and 1.4 m thick.

The wind energy heat pump system has an automotive air conditioning compressor directly driven by a v-belt drive (Figure 19). The compressor will operate from speeds of 2000 r/min to 3000 r/min, with the maximum volumetric efficiency occurring near 2500 r/min. The v-belt drive has a 76 cm pitch diameter pulley mounted on the turbine shaft and a 11.7 cm pitch diameter pulley mounted on the compressor shaft, to obtain a 6.5:1 speed increase.

Performance Evaluation

Testing wind turbines is difficult because of the complexity in obtaining the average wind speed over the area of the rotor. Because wind varies greatly in direction and speed over short time durations (Sheldahl, et al., 1980), the effective wind speed over the surface of the turbine is not equal to the wind speed measured at the anemometer (Johnson and Babb, 1979). Errors in test data are also introduced by the anemometer response time to changing wind speeds and by the inertia of the wind turbine (Sheldahl and Blackwell, 1977). Error in measuring wind speed is amplified, since wind power is proportional to the wind speed cubed. Consequently, power output from a turbine generally does not correlate well with corresponding power available in the wind (Johnson and Babb, 1979).
Figure 18. Caliper disc brake assembly.

1 Mechanical Actuator
2 Disc
3 Hub
4 Adaptor Sleeve
5 Lockwasher
6 Locknut
7 Mounting Bracket
8 Spacer Plate
9 Bracket Support
10 Bracket Anchor
11 Lever
Figure 19. Turbine drive.

Description

1 Large Sheave
2 Small Sheave
3 V-Belt
4 Air Cond Compressor
5 Vibration Isolator
6 Compressor Platform
7 Brace
8 Drive Shaft
9 Shaft Spacer
To increase the reliability of the data, wind speed should be measured at the rotor equator height and at a point two turbine-diameters away from the axis of rotation and perpendicular to the normal wind direction (Sheldahl, et al., 1980). Wind velocities should be measured at the centerline height of the turbine because empirical equations for predicting wind velocities at various elevations do not adequately adjust for various terrain effects. The one-seventh power law used for predicting wind speed at various heights has been shown to be in error by 10 percent on level, treeless land and up to 200 percent in hilly terrain (Clark, 1980). Locating the anemometer away from the turbine in this manner limits the influence of the rotor on the anemometer (e.g. the winds are usually from the north or south so the anemometer is located two turbine-diameters east or west of the turbine axis). Data should only be taken when the wind is from its usual direction.

However, even with proper location of the anemometer wind data are difficult to analyze because of their variability. Therefore an averaging technique called the "method of bins" was developed and found to be a reliable way to determine performance characteristics of constant-speed Darrieus systems.

To utilize this method wind speed and corresponding torque output are recorded at rates from one to ten datum samples per second with the torque measurements being summed into "velocity bins" as determined by the complimentary wind velocity. Velocity bins are ranges of wind speeds, (e.g. 4.5 to 5.0 m/s) for which the torque measurements and the number of increments are summed. With these values
an average torque can be calculated for a particular range of wind speeds. In a constant-speed system power can be determined at a given wind speed because rotational speed is known (Sheldahl and Blackwell, 1977). To sample and store data at the rates necessary for reliable analysis a minicomputer is needed (Clark, 1980).

Researchers have tested the 5-m Darrieus operated in a constant-speed mode. Sandia laboratories tested a 5-m Darrieus with NACA-0015 blades at three different rotational speeds (Figure 14). The Darrieus maintained constant rotational speed when connected to a synchronous generator which, in turn was connected to a power grid capable of maintaining constant frequency (Banas and Sullivan, 1976). Turbine torque and rotational speed were measured by a torque transducer coupled into the drive train. The couplings help protect the sensor from vibrations, misalignment and torque ripple (Worstell, 1978). Torque lost through bearing friction and belt losses was also calculated and added to the averaged torque readings to obtain performance of the rotor, independent of system design (Sheldahl and Blackwell, 1977). The maximum power coefficient, defined as the ratio of the actual power extracted to the power available from the wind in the cross-sectional area of the rotor, was 0.392 at a rotational speed of 150 r/min and a tip speed ratio of 5 (Figure 14).

Testing the Darrieus in a variable-speed mode is more difficult because turbine torque and rotational speed vary with changes in wind speed. Variable-speed tests were conducted in wind tunnels where a constant wind speed was maintained (South and Rangi, 1972). It is possible that through the use of high speed data acquisition equipment,
data for a variable-speed system under free-air conditions could be processed by a form of the method of bins. However, this approach is believed impractical because of the large number of bins it would take for adequate analysis of a variable-speed system (Sheldahl, 1982). An indirect method of analyzing variable-speed wind turbines is by using the efficiency versus tip speed ratio graph (Figure 14). By assuming that the efficiency versus tip speed ratio curve is constant, a relationship can be developed between torque and rotational speeds for various wind speeds (Figure 15). Since efficiency varies as the blade Reynolds number changes for a given tip speed ratio, there will be some error in the derived curves. However, this method gives results that are currently the best available for a variable-speed system (Sullivan, 1982).

Karnitis (1980), using the variable-speed performance curves derived by Sandia Laboratories for a Savonius-Darrieus turbine, determined regression coefficients for a proposed Savonius-Darrieus system (Figure 20). However, there are several significant differences between the turbines. The Sandia Laboratories turbine has a chord length of 190 mm and a maximum efficiency of 0.36 while the proposed turbine has a chord length of 152 mm and a maximum efficiency of 0.35. Consequently, the performance curves derived by Karnitis (1980) do not accurately predict the performance of the proposed Darrieus system.
Figure 20. Performance characteristics of a hybrid Darrieus-Savonius wind turbine and speed-dependent loads for 168.8, 142.6 and 100 cm³/rev reciprocating compressors at constant wind speeds (m/s).
PROCEDURE

A cantilevered Darrieus was designed and sized to be coupled to a variable-speed heat pump for farm heating applications. The turbine was instrumented and tested under varying wind and rotational speed conditions. Performance of the variable-speed system was determined and evaluated. Efficiency from variable-speed operation was determined and compared to theoretical efficiency resulting from various constant-speed operations.

Darrieus System Design and Construction

Darrieus Design and Construction

The original Darrieus design described in the literature review (Karnitis, 1980) was modified to reduce costs and simplify construction while maintaining the structural requirements necessary for safe operation. Modifications were incorporated into the design of the bearings, rotor, torque tube, tower, brake and foundation.

Small bearings were used because of cost considerations. A structural analysis determined that a 127 mm diameter and a 64 mm diameter shaft provided nearly the same structural support as the 165 mm diameter x 12.7 mm torque tube for the upper and lower bearing locations, respectively. By using a 140 mm diameter x 6.4 mm sleeve and a press fit of the 127 mm diameter shaft a suitable coupling was constructed to mount the top bearing. A similar process was followed for the lower bearing location except the solid shaft was tapered to reduce stress concentrations (Figure 21).

The turbine torque tube was originally designed as a continuous 8.2 m x 165 mm diameter x 12.7 mm aluminum shaft but could only be obtained in
3.7 m sections. Because a 4.6 m section was needed for the rotor a 0.9 m section was welded to a 3.7 m section. Couplings, as described in the previous paragraph, were used to obtain the needed length for the torque tube.

Tower design was simplified for ease in construction, leading to savings of time and labor, while still maintaining adequate structural strength. Strap steel was used for bracing the tower and lower bearing instead of angle steel and channel steel, respectively. The top bearing was supported by a 12.7 mm thick plate of steel, welded to the top of the tower and supported by angle steel welded to the tower legs.

The Savonius was removed from the Darrieus because it was unnecessary for testing of the Darrieus. Since the primary objective was to test the Darrieus operated in a variable-speed mode, it was decided to start the turbine by hand. The Savonius would also have affected efficiencies of the Darrieus making it more difficult to compare data reported from similar Darrieus turbines.

The original brake design called for a mechanical caliper disc brake operated manually. Braking for a variable-speed Darrieus should be automatic because, if overspeed conditions occur when the operator is not present, the turbine may be damaged. Thus, pneumatic caliper brakes were selected (Figure 21). These brakes were failsafe in that if there was a power supply or air supply interruption the brakes would engage. During testing the brakes were manually operated, but the brakes are designed to perform equally well in an automatic control system.
The original foundation design required 7.4 m$^3$ of concrete, which was considered unacceptably expensive. The revised design (Figure 22) extends the tower's legs 1.4 m into the foundation and anchors them with steel reinforced concrete, 1.8 m x 0.3 m diameter. A 2.1 m x 2.1 m x 0.3 m pad of steel reinforced concrete forms the base for the turbine pad. This design uses 60 percent less concrete without significantly reducing the strength of the foundation.

Blade connections used the original design (Figure 17) as proposed by Karnitis (1980). This design is no longer recommended by Darrieus manufacturers because the blades are held in a rigid position which stresses the welds and may cause them to fail after a period of use. Because of the difficulty in obtaining alternate means to hold the blades, it was decided to use the original design, since the Darrieus would be used less frequently than commercial models.

System Design

The Darrieus was constructed using the described design and mechanically coupled to a hydraulic dynamometer (Figure 23). The Darrieus was started manually, and when it reached operating speeds, loads were applied using the dynamometer. By using the hydraulic dynamometer as a loading device simulation of variable-speed system operation was obtained.

The hydraulic dynamometer was connected to the turbine drive train by a right angle gear box that increased the rotational speed by 1.25 (Figure 24). Input power to the dynamometer is used to drive reciprocating hydraulic pumps that force oil through a manually
Figure 21. Lower bearing and brake assembly for Darrieus wind turbine.

Figure 22. Foundation for Darrieus wind turbine while under construction.
Figure 23. Hydraulic dynamometer mechanically coupled to Darrieus wind turbine.

Figure 24. Right angle gear box with torque transducer and couplings.
controlled valve. By adjusting the valve a wide range of loads can be obtained. Because turbine rotational speeds varied with changing wind speeds for a constant valve setting a relationship was determined between power absorbed by the dynamometer and input rotational speeds. According to the M & W Gear Company (1982), doubling the input rotational speed increased the power absorbed by approximately 2.5 to 3. A more accurate relationship could not be obtained since data on the dynamometer are based on the higher rotational speeds and horsepower requirements of tractors.

During operation the control valve setting on the dynamometer remained constant except when there were significant changes in wind speed. The valve setting would then be changed to vary the load on the Darrieus so that better utilization of the wind power was realized or overspeed of the rotor was prevented. Varying the load, in response to changing wind speed, was deemed a reasonable method of operating a variable-speed system.

Testing Procedure

Instrumentation

Instrumentation consisted of a cup anemometer to measure wind speed, a torque transducer to measure turbine torque and rotational speed, and a microprocessor based acquisition system to collect data. The cup anemometer was located two turbine-diameters west of the Darrieus and at the midheight of the rotor. Since the turbine was operated when winds were primarily from the north or south, it is believed that the measured wind speeds were representative of wind
velocities at the Darrieus. The cup anemometer, accurate within one percent, was deemed suitable for this study (Cambell, 1982).

Turbine torque and rotational speed were determined by a torque transducer. The transducer was connected into the drive train, below the lower bearings, by flexible couplings, protecting it from shaft misalignment and vibrations (Figure 24). Accuracy of the torque transducer was within one percent according to manufacturer specifications.

Density of the air was calculated by measuring the barometric pressure and temperature. The barometric pressure was determined at the South Dakota State University weather station and was considered constant during a test period. Temperature was measured every 90 seconds using a copper constantan thermocouple.

Data acquisition was accomplished using a digital voltmeter, scanner and minicomputer. Output voltages from the transducers were measured by the digital voltmeter with the scanner reading these measurements at a rate of up to 20 per second. The voltmeter and scanner were controlled by programming the minicomputer appropriately. Data measurements were recorded on data tapes capable of storing over 34,000 readings.

Test Design

Testing of the variable-speed system was conducted in two stages. Since this was believed to be the first cantilevered Darrieus operated in a variable-speed mode, caution was used during initial operation to determine the ranges of rotational speeds over which
the Darrieus could be safely operated and to learn how the turbine reacted to changes in wind speed. After operational limitations were known, the turbine was operated over a wide range of rotational speeds and wind speeds to determine performance characteristics.

Rotational speed limitations of the turbine were found by on-line monitoring turbine rotational speeds and by checking the results to determine at which rotational speeds limitations existed. Rotational speeds were gradually increased, until it was judged that higher rotational speeds would be unsafe. A measure of the dynamic response of the turbine was obtained by measuring wind speed, turbine torque and turbine rotational speeds over a five second interval and averaging the values. The averaged values were used to calculate wind power, turbine power and efficiency. All measured and calculated values, the number of readings per time interval, and actual time interval length were then stored on data tapes.

After performance limitations were known, the Darrieus was monitored continuously under various operating conditions. Barometric pressure and temperature were recorded at the beginning of a test period, while rotational speed, turbine torque, and wind speed were continuously measured during the test period. Filled data tapes were returned to the Agricultural Engineering Data Acquisition Center for analysis.

Data Analysis

In order that the results of the study could be compared to previous research, test data were standardized for density fluctuations
and friction losses. Correcting for friction losses gave rotor efficiencies that are independent of the overall system arrangement. Data normalized to a standard density prevented density fluctuations from biasing the results. Torque data were normalized for a density of 1.15 kg/m$^3$ and were corrected for a bearing friction torque of 5.5 N-m.

To adequately describe the performance of the Darrieus system, graphs of turbine torque and turbine power as a function of turbine rotational speed were needed. Through the use of a statistical method called the "method of bins" and a minicomputer, adequate performance curves were obtained. Using the values determined, equations relating turbine torque and power to turbine rotational speed were developed using least square, multiple regression techniques.

Efficiency of the system was determined as a function of the tip speed ratio. Efficiency was also determined by graphing turbine power as a function of wind speed using the statistical method of bins. The derived graph was compared to curves which depict output from this wind turbine operating at efficiencies of 20, 30 and 40 percent respectively. Efficiency of the turbine during the test period was also calculated by summing turbine power and available wind power over the testing period.

Variable-Speed Model

A variable-speed Darrieus system was modeled using data from Sandia Laboratories' 5-m Darrieus. Since the Sandia turbine and the test turbine have the same configuration and blades, it was assumed
that operating characteristics were similar. Differences in means of support, guyed versus cantilevered, and in blade attachments were assumed not to significantly affect performance.

There are two basic methods of modeling a variable-speed Darrieus. The models can be shown as a series of performance curves for various wind speeds (Figure 15), or as a single performance curve for a selected tip speed ratio. By utilizing constant-speed data from Sandia Laboratories 5-m Darrieus, a reasonable estimate of the performance curves can be obtained by both methods. However, since a variable-speed Darrieus should operate at a near constant tip speed ratio for optimal efficiency, the single performance curve for a selected tip speed ratio was deemed the most useful model.

To determine the performance curve for a selected tip speed ratio the efficiency versus tip speed ratio curve must be considered constant for a range of rotational speeds (Figure 14). Because there is a Reynolds number effect, the efficiencies were adjusted according to which range of rotational speeds were being considered. Since there is a relatively constant efficiency for a given tip speed ratio and range of rotational speeds, wind speed, turbine power, and turbine torque can be calculated for a selected rotational speed. Relationships between turbine torque or turbine power can then be plotted as a function of turbine rotational speed for a selected tip speed ratio.

Optimal combinations of turbine torque and rotational speeds for a variable-speed Darrieus were determined by selecting a tip speed ratio that gives high efficiencies. For a given wind speed
there will then be a rotational speed that corresponds to the optimal operating conditions. For this study a tip speed ratio of five was selected.

**Variable-Speed Versus Constant-Speed Operation**

Comparison of the efficiency of variable-speed Darrieus systems to constant-speed Darrieus systems is very important. Currently there is no reliable estimate of the improvement in efficiency one may expect by operating the turbine in a variable-speed mode. An economic comparison between operating the Darrieus in a variable-speed mode versus a constant-speed mode requires knowledge of this efficiency improvement.

The theoretical efficiency of the cantilevered Darrieus operated in a constant-speed mode was found by using the efficiency versus tip speed ratio data from Sandia Laboratories 5-m Darrieus (Figure 14), and the measured wind speeds during testing. By assuming a constant rotational speed, various tip speed ratios were obtained according to the wind conditions during testing. With the calculated tip speed ratios and the data relating efficiency to tip speed ratios, an efficiency was obtained for a constant-speed Darrieus system.

Rotational speeds of 125, 137.5 and 150 r/min were used in the constant-speed analysis so that efficiencies did not have to be adjusted for Reynolds number effects and yet were practical for constant-speed systems. To determine if these speeds adequately represented a constant-speed Darrieus system for Brookings, South Dakota an optimal constant rotational speed was determined. This rotational
speed was based on a wind speed that gave highest annual power availability, and a tip speed ratio that gave highest efficiencies. The optimal wind speed was found by using a derived power distribution table for Brookings, South Dakota (Table 1). By selecting a wind speed for highest power output in conjunction with a tip speed ratio for highest efficiencies a "best" rotational speed for a constant-speed Darrieus was obtained.

With efficiencies of the Darrieus known, as calculated for various constant rotational speeds, a comparison was made with the efficiency of the Darrieus operated in a variable-speed mode. Conclusions were drawn on the effect different operating modes have on the efficiency of the Darrieus.
RESULTS

A cantilevered Darrieus was designed and sized to be mechanically coupled to a heat pump for agricultural applications. The Darrieus was constructed during the summer and fall of 1981. Testing of the Darrieus under varying wind and rotational speed conditions was conducted between May and July of 1982. Performance curves, which show turbine torque and power as functions of turbine rotational speed, were developed from test data for the variable-speed Darrieus. Efficiency of the variable-speed system was compared to the efficiency that would have been obtained from the same Darrieus and wind conditions under different constant-speed operating procedures.

Design and Construction

The cantilevered Darrieus system operated satisfactorily at rotational speeds up to 180 r/min. Above rotational speeds of 180 r/min failure may occur with the turbine torque tube because of severe vibrations caused by a mass imbalance of the rotor. Failure may also occur with the blade connections and the turbine bearings during extended use.

Vibrations due to a mass imbalance limited speeds to approximately 120 r/min, but by using a counterweight the vibrations were reduced and the system operated satisfactorily at speeds up to 188 r/min. The cantilevered Darrieus is susceptible to vibrations caused by a mass imbalance, and the vibrations are accentuated by the relative flexibility of the aluminum torque tube. A slight mass imbalance occurred when a four-m pipe was welded to one-m pipe to obtain the
five-m torque tube shaft on which the turbine blades were mounted. This weld created a mass imbalance which caused vibration problems at higher rotational speeds. Mass imbalance can be reduced by using a continuous shaft for the torque tube and by machine balancing. The aluminum torque tube, because of its relatively low modulus of elasticity, deflects more than a steel shaft of similar structural strength. Since an equivalent-strength, steel torque tube has higher structural stiffness, the amplitude of the vibrations would be reduced with a torque tube of steel instead of aluminum.

Savings occurred with the use of smaller bearings. Bearing costs for the original design were approximately $4000, while bearings costs for the modified design were $1190 for the top bearing and $90 for the lower bearing. The design for the top bearing worked satisfactorily during testing, but it is not recommended for continuous operation over several years because failure may occur with the bearing or turbine torque tube. Bearings used in similar cantilevered Darrieus designs have failed due to the larger fluctuating loads inherent in this design as compared to guyed turbines (Vosburgh, 1981). Bearings should be press-fitted to the turbine torque tube to minimize any relative motion that may cause the bearings to fail. However, press-fitted bearings may cause the torque tube to fail because of fretting corrosion. Fretting corrosion occurs because press-fitted joints are subjected to reverse bending, when a point on the joint is alternating from tension to compression (Spotts, 1970). Also stress concentrations are introduced, especially at the top bearing location, that may accelerate this process. Consequently, the joint
connection for the upper bearing location is not recommended. A continuous shaft should be used and the bearing should be press-fitted onto it. More research will be needed to verify the reliability of this component, or to produce a more satisfactory solution. The lower bearing design as modified (Figure 21) is satisfactory since it results in minimal costs in labor and structural strength while saving approximately $2000 in bearing costs.

The design for the blade connections (Figure 17) is no longer recommended by Darrieus manufacturers because the design has failed in actual use. Failure occurs in this design because the blades are held in a fixed position such that blade vibrations stress the welds of the fixture causing them to fail after a period of use. Failure did not occur with any of the welds during testing of the Darrieus but may occur with extended use. For long term operation fabricated blade holders produced by manufacturers of Darrieus turbines are recommended.

**Test Procedure**

Testing procedure for the variable-speed Darrieus achieved all objectives. Step-wise loading was accomplished effectively using the hydraulic dynamometer. Turbine torque, turbine rotational speed and wind speed were accurately measured several times a second, which is suitable for wind turbine studies. Data were analyzed using the statistical method of bins to develop useful efficiency and performance information.

Step-wise loading, using a hydraulic dynamometer, (Figure 23)
was adequate for an initial study of the variable-speed Darrieus system. Load was varied in increments to match the load to the turbine power output. However, operator judgement was required to load the Darrieus in order to operate the system for best efficiencies. Also, distinct step-wise loads could not be applied to the Darrieus during testing because of the difficulty in measuring the load torque applied to the Darrieus and the tendency for the load torque to increase with increasing rotational speeds. The step-wise loading method applied to the Darrieus may have been more effective than that indicated in Figure 8, but was less effective than the variable-ratio transmission loading method (Figure 9).

Data acquisition equipment proved suitable for analyzing variable-speed Darrieus systems. Data were measured, using transducers with stated accuracies within one percent, at rates of up to 20 measurements per second. All turbine rotational speed and wind speed values were reliable, but 0.7 percent of the torque data were erroneous because the values exceeded 1,000,000 N-m, while the majority of the torque values were between -10 and 160 N-m. Erroneous torque data are believed to have occurred from the vibrations the torque transducer experienced in the turbine drive train. This problem may be controlled by using more flexible couplings than the chain couplings (Figure 24), which were used to protect the transducer.

Through the use of the statistical method of bins, averaged turbine torque and turbine power values were obtained for a range of turbine rotational speeds. Regression equations of turbine torque
and power as functions of turbine rotational speed had $R^2$ values in excess of 0.97. Although this was suitable for the study, more accurate results can be obtained from this method by keeping the tip speed ratio more nearly constant. For each range of rotational speeds selected in the study there was variation in the tip speed ratio (Figure 30). Consequently, there was variation in the wind power that occurred for a range of rotational speeds, and therefore variations in the turbine torque and turbine power measurements. If the tip speed ratio were constant, wind speed would always be proportional to the rotational speed. If the range of rotational speeds were small (e.g. less than or equal to 10 r/min) the difference in wind speeds would also be small, and wind power availability would be more constant for the range of rotational speeds than for a variable-speed system with a less constant tip speed ratio. In using the method of bins as a means to determine the performance of a variable-speed Darrieus system, the accuracy will improve as the tip speed ratio becomes more constant.

Efficiency of the Darrieus was determined by three methods: (1) efficiency versus tip speed ratio, (2) turbine power versus wind speed, and (3) summed turbine power divided by summed wind power. Averaged efficiencies were deemed more reliable because instantaneous efficiencies can be meaningless (e.g. wind speed may decrease quickly while turbine rotational speed responds more slowly resulting in efficiencies higher than the theoretical maximum efficiency of 59 percent). Erroneous efficiencies were produced by the efficiency versus tip speed ratio analysis because at the high tip speed ratios there were
few measurements. This method is also unsuitable for analyzing efficiencies of variable-speed systems because variable-speed systems try to maintain a constant tip speed ratio.

The variable-speed model, used to evaluate the performance of the variable-speed Darrieus is adequate for the study. This model was based on a five-m Darrieus turbine operating in a variable-speed mode at a constant tip speed ratio of five for maximum power output.

Efficiency for the model was not considered constant, but was increased with increasing rotational speeds as shown by the data used to determine the model (Figure 14). However, efficiencies were considered constant below and above rotational speed values of 125 and 150 r/min respectively, because the decrease or increase in efficiency due to a decrease or increase in rotational speed could not be reliably determined. Consequently, below rotational speeds of 125 r/min, the model will predict values slightly higher than can be expected while above rotational speeds of 150 r/min the model will predict values slightly lower than can be expected. To improve the model, more research will be needed on the effect Reynolds number, a function of rotational speed, has on the efficiency of the Darrieus.

**Performance Evaluation**

Testing of the Darrieus in a variable-speed mode took place from May 1982 to July 1982. Approximately five hours of testing were used to determine rotational speed limitations of the rotor and turbine response to changing wind speeds. Between 20 and 25 hours of turbine operation were used to determine the performance character-
Test Observations

Operating the Darrieus in a variable-speed mode posed no major problems. Vibrations due to resonance were found at shaft rotational speeds of approximately 50 and possibly 180 r/min. It was not determined if the vibrations at 180 r/min were due primarily to mass imbalance or resonance effects or a combination of both. In starting and stopping the turbine, vibrations were not noticed unless the turbine operated near resonance frequency for several seconds. It appears that resonance conditions will not cause vibrations during starting and stopping, since shaft speeds change rapidly. However, if resonance conditions exist in the normal operating range of the Darrieus, the turbine may stay at the critical shaft speed for several seconds, causing increased vibrations.

Turbine responses to changing wind speeds are shown in Figures 25 and 26. A change in wind speed would change turbine torque, but the change in shaft speed would lag by up to five seconds. Since the turbine did not respond instantaneously with changing wind speeds, tips speed ratios varied from an optimum and efficiencies were lowered.

In determining the performance characteristics of the variable-speed Darrieus, over 38,100 readings each of turbine torque, turbine rotational speed and wind speed were taken. Wind speed data ranged up to 15.3 m/s with 99.7 percent of the data between 0 and 12 m/s (Figure 27). Rotational speed data reached a maximum of 188 r/min with 98.2 percent of the data between 0 and 170 r/min (Figure 28). No maximum
Figure 25. Representative time histories of 5-m Darrieus torque, rotational speed, and site wind velocity.
Figure 26. Representative time histories of 5-m Darrieus power output and site wind power.
Figure 27. Frequency distribution for wind data.
turbine torque value was determined but 92.8 percent of the values ranged from -10 to 160 N-m (Figure 29).

In reviewing the data measured, an unusual frequency distribution of the rotational speeds was noted (Figure 28). A far larger frequency of rotational speeds between 60 and 70 r/min than what would normally be expected was found. This may have been caused by the loading put on the Darrieus, since the turbine torque and turbine rotational speed frequency curves are similar (Figures 28 and 29).

During testing it was also noted that at wind speeds near 4 m/s the Darrieus would appear to be overloaded by the friction effects of the load system, without any load being applied by the operator. This may have caused the Darrieus to operate at rotational speeds lower than normal under similar wind conditions. It appears that in testing a variable-speed system, friction should be kept to a minimum so that loading can be satisfactory at low wind speeds.

The tip speed ratio frequency distribution curve was shifted toward lower tip speed ratios and included a wider range than what was expected (Figure 30). This shift occurred because of the overloading of the turbine at high wind speeds to prevent overspeeding of the turbine. Consequently, the turbine turned slower than it normally would at the high wind speeds, and the tip speed ratio as well as the turbine efficiency decreased. The tip speed ratio distribution was spread out because the turbine rotational speed could not respond instantly to changing wind speeds and because of the effect of the step-wise loading. By decreasing the inertia of the system, the
Figure 28. Frequency distribution for turbine rotational speed data.
Figure 29. Frequency distribution for turbine torque data.
Figure 30. Frequency distribution for tip speed ratios determined from wind and turbine rotational speed data.
turbine can respond more quickly to changing wind speeds and the efficiency of the system will increase. Step-wise loading caused variations in the tip speed ratio since the loading was not continuously varied to match the power output of the turbine. By using a variable-ratio transmission and multiple compressors loads can be applied to the turbine that keep the tip speed ratio closer to an optimum.

Data Analysis

Regression equations using multiple, least square techniques were used to fit the data, as determined by the statistical method of bins. The tested Darrieus system operated near optimal conditions, as predicted by the derived model, up to rotational speeds of 120 r/min (Figure 31). Above 120 r/min the Darrieus system became less efficient. Figure 32 shows the decreasing efficiency of the Darrieus at high wind speeds, corresponding to high rotational speeds. Efficiency of the Darrieus is above 30 percent for wind speeds less than 8.5 m/s; above this wind speed efficiencies decrease to nearly 20 percent.

Efficiencies decreased with increasing rotational speeds and wind speeds because the rotor was braked to prevent overspeeding and because of the inertia effect of the turbine. Loadings were increased on the Darrieus to prevent rotational speeds from becoming to high (Figure 33). If the Darrieus were operated at higher maximum rotational speeds, efficiencies would have increased since the turbine would not have to be loaded down as often or as severely. For example, in a wind of 10 m/s the turbine should turn at 209 r/min to maintain a highest efficiency of 39 percent. However, since the turbine can
Figure 31. Performance characteristics, relating turbine power to turbine rotational speed, for the variable-speed Darrieus wind turbine.
Figure 32. Actual power output from the variable-speed Darrieus wind turbine as compared to theoretical power output at efficiencies of 20, 30 and 40 percent.
Optimal Performance: 
Actual Performance: 
Torque (N·m) = -4.4 + 0.00515 (r/min)
$R = 0.873$

Figure 33. Performance characteristics, relating turbine torque to turbine rotational speed, for the variable-speed Darrieus wind turbine.
only operate up to 180 r/min the tip speed ratio decreases to less than 4.3 and the corresponding efficiency becomes less than 35 percent. Perhaps a more important factor is the inertial effect of the turbine. Since the turbine rotational speed cannot respond instantly to changing wind conditions, the tip speed ratio will not always be optimal, and efficiencies will be lowered (Figures 25 and 26). The rotor would have responded more quickly to changing wind conditions, if the load had been decreased between rotational speeds of 120 to 180 r/min, and if the inertia of the system would have been less, but the corresponding increase in efficiency was not determined.

Comparison Between Variable-Speed and Constant-Speed Operation

Efficiency of the variable-speed system was compared to the efficiency that would have been obtained from the same Darrieus and wind conditions under constant rotational speeds of 125, 137.5 and 150 r/min. The constant rotational speeds selected for the study, adequately represent an optimal constant rotational speed system for Brookings, South Dakota wind conditions. A 19 percent improvement in power output was obtained by operating the Darrieus in a variable-speed mode as compared to a near optimal constant rotational speed of 150 r/min.

An optimal constant rotational speed of 149 r/min was selected for Brookings, South Dakota. The rotational speed was based on a wind speed of 7.15 m/s for maximum available wind power (Table 1) and a tip speed ratio of 5 for highest efficiencies (Figure 14). The wind power frequency distribution was derived using the frequency distribution for wind speeds as determined by Lytle (1982) for
Table 1. Wind power distribution for Brookings, South Dakota at 10 m.*

<table>
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<tr>
<th>Wind Speed, m/s</th>
<th>Frequency, percent</th>
<th>(Wing Speed)³ Frequency</th>
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<tr>
<td>0.45</td>
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<tr>
<td>14.75</td>
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*Based on hourly wind data from January 1, 1970 to December 31, 1980.
Variable-speed operation of the Darrieus was 19 percent more efficient than the constant-speed system operating at a near optimal rotational speed of 150 r/min. Variable-speed operation resulted in an efficiency of 31.8 percent, corresponding to a potential power output of 2670 kW-h annually (as determined from Table 1). Constant-speed operation at rotational speeds of 150, 137.5 and 125 r/min resulted in theoretical efficiencies of 26.7, 25.4 and 23.1 percent, respectively. Improvement in efficiency for the variable-speed system was primarily because the tip speed ratio stayed near an optimum of 4.0 to 5.0, (Figures 30, 34, 35 and 36) and because it operated at rotational speeds higher than 150 r/min during high wind conditions. Though the 150 r/min constant-speed data showed the largest spread in the tip speed ratio frequency distribution, the 150 r/min had the highest efficiencies among the constant-speed systems. This was because the 150 r/min constant-speed Darrieus can more effectively use the greater power available at higher wind speeds, compared to the lower-speed turbines.

Efficiency of the variable-speed Darrieus system would be higher if the turbine was operated to a higher maximum rotational speed and if loading was better matched to the Darrieus. Greater rotational speeds are possible if vibrations can be controlled by eliminating the mass imbalance and by stiffening the structure. Structural stiffness would be increased by using a steel torque tube instead of aluminum and by using guy wires as a means of support.
Figure 34. Frequency distribution for tip speed ratios determined from wind data and a constant turbine rotational speed of 125 r/min.
Figure 35. Frequency distribution for tip speed ratios determined from wind data and a constant turbine rotational speed of 137.5 r/min.
Figure 3B. Frequency distribution for tip speed ratios determined from wind data and a constant turbine rotational speed of 150 r/min.
However, a steel torque tube will increase the inertia of the turbine causing a slower response to changing wind speeds, while guy cables may lead to troublesome vibrations.

Loading the turbine properly was difficult because the optimal turbine torque curve is a function of the square of the turbine rotational speed. Since torque required by the dynamometer increased by approximately 1.25 to 1.5, when the turbine rotational speed doubled, optimal load conditions could not be obtained. However, by step-wise varying of the load, the turbine performance was near optimal until the higher rotational speeds were reached. This method of loading has been proposed by Liljedahl and Kluter (1982), (Figure 8). Loading by this method can further be improved by using variable-ratio transmissions in conjunction with the multiple compressors (Figure 9). Such a system will provide the needed torque characteristics to obtain maximum power output from a variable-speed Darrieus.
CONCLUSIONS

The following conclusions were reached as a result of this study:

1. Cantilevered support of the Darrieus was adequate for shaft rotational speeds less than 180 r/min. Higher rotational speeds were not achieved because of excess vibrations caused by a mass imbalance of the rotor.

2. Bearing costs for the cantilevered Darrieus were decreased by nearly $2000, without any loss of structural reliability, by mounting the lower turbine bearing on a 64 mm shaft instead of a 165 mm diameter x 12.7 mm wall thickness tube.

3. Splicing the turbine torque tube resulted in mass imbalances that caused vibrations, and stress concentrations which reduced the strength of the tube.

4. The aluminum torque tube resulted in larger vibrations than would have occurred with a similar strength steel torque tube.

5. The hydraulic dynamometer effectively loaded the Darrieus during variable-speed testing.

6. Performance of the variable-speed Darrieus was reliably determined using the statistical method of bins.

7. Optimal performance for a variable-speed, 5-m Darrieus system was determined.

8. Vibrations due to resonance were found at shaft rotational speed of approximately 50 and possibly 180 r/min, but posed no problem as operating speeds were above and below these values, respectively.
9. Turbine rotational speed lagged changes in wind speed by up to five seconds.

10. The variable-speed Darrieus system operated near optimal efficiency to rotational speeds of 120 r/min. Above 120 r/min, efficiencies decreased because the rotor was braked to prevent overspeeding of the turbine and because of the inertial effect of the turbine.

11. The optimal constant rotational speed for Brookings, South Dakota wind conditions was found to be 149 r/min.

12. Variable-speed operation of the Darrieus resulted in a 19 percent improvement in power output over a near optimal, 150 r/min constant-speed system.

13. Variable-speed operation of the Darrieus resulted in an efficiency of 31.8 percent with a potential power output of 2670 kW-h annually. Constant-speed operation of the Darrieus at rotational speeds of 150, 137.5 and 125 r/min resulted in theoretical efficiencies of 26.7, 25.4 and 23.1 percent.

14. Efficiency of the variable-speed Darrieus system would be higher if the turbine operated at a higher maximum rotational speed and if loading were optimal.
The economic viability of wind energy for agricultural applications is highly dependent on initial costs and total energy produced. Cantilevered Darrieus wind turbines are one of the most promising turbines because of relative low capital costs inherent in the simple design. Darrieus rotors have higher efficiencies by operating in a variable-speed mode rather than in a constant-speed mode. Utilizing the direct mechanical energy generated, rather than first producing electricity, eliminates losses caused by the intermediate generation of electricity. However, operating the Darrieus in a variable-speed mode may pose problems in limiting vibrations, applying loads and controlling rotational speeds.

A Darrieus was designed and constructed to be mechanically coupled to a heat pump for agricultural applications. This design minimized the cost of a cantilevered Darrieus and was suitable for testing purposes. All turbine components operated satisfactorily during testing but the upper bearing, blade attachments and torque tube may fail after extended use.

Performance characteristics of a variable-speed Darrieus were determined by measuring wind speed, turbine torque, and turbine rotational speed, while the Darrieus operated. A hydraulic dynamometer was used to step-wise load the Darrieus to maintain high efficiencies. Performance curves were found by using the statistical method of bins and multiple, least square regression analysis. A model of an optimal variable-speed Darrieus system was used to evaluate the turbine
Cantilevered support of the Darrieus was adequate for shaft rotational speeds less than 180 r/min. Higher rotational speeds were not possible because of vibrations that developed due to a mass imbalance of the rotor. Resonance conditions were found at rotational speeds of 50 and possibly 180 r/min. The variable-speed system operated near the predicted optimum to a rotational speed of 120 r/min, but above 120 r/min efficiencies decreased because the rotor was overloaded to prevent overspeeding and because of the inertial effect of the turbine.

Efficiency from variable-speed operation was determined and compared to theoretical efficiency resulting from various constant-speed operations under the same wind conditions. Variable-speed operation of the Darrieus resulted in 19 percent improvement in power output over a near optimal constant-speed system using a rotational speed of 150 r/min. Variable-speed operation resulted in an efficiency of 31.8 percent, with a potential power output of 2670 kW·h annually, while constant-speed operation at rotational speed values of 150, 137.5 and 125 r/min resulted in efficiencies of 26.7, 25.4 and 23.1 percent, respectively. Efficiency of the variable-speed system would have been higher, if the turbine had operated at higher rotational speeds and if a more optimal method of loading were used.
REFERENCES


Rollins, J.P. Personal communication. Department of Mechanical and Industrial Engineering, Clarkson College of Technology, Potsdam, New York.


